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*Applications of Reliability Methods in Design and Analysis*

Velarde, Joey

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## APPLICATIONS OF RELIABILITY METHODS IN DESIGN AND ANALYSIS

**BY**
**JOEY VELARDE**

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# Probabilistic Design of Offshore Wind Turbine Support Structures

Applications of Reliability Methods in Design and Analysis

Ph.D. Dissertation

Joey Velarde

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*Department of Civil Engineering*
*Faculty of Engineering and Science*
*Aalborg University*

AALBORG UNIVERSITY
DENMARK

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PhD supervisors: Prof. John Dalsgaard Sørensen
Aalborg University, Denmark

M. Sc. Claus Kramhøft
COWI A/S, Denmark

PhD committee: Professor Lars Damkilde (chairman)
Aalborg University

Professor Michael Muskulus
NTNU

Professor Henrik Bredmose
DTU Wind Energy

PhD Series: Faculty of Engineering and Science, Aalborg University

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# Summary

There is a growing interest in applications of probabilistic methods in design of offshore wind turbines. As opposed to the classical, deterministic design approach, the probabilistic design approach has the advantage of being able to account for site-specific information, experimental test results and availability of better models. This often leads to more cost-effective design solutions. In order to apply a probabilistic approach in design of offshore wind turbine support structures, identification of the most significant parameters and development of a probabilistic framework become necessary.

A typical offshore wind turbine aero-hydro-servo-elastic load model integrates different submodels that represent the metocean environment, geotechnical conditions, wind turbine control and wind turbine structure. These require a large number of input parameters, each estimated with different degrees of uncertainty. But not all uncertainties are equally important. For a complex, nonlinear system with a large number of uncertain parameters, global sensitivity analysis techniques were used to establish the most significant parameters. By focusing on the few important parameters, the succeeding probabilistic analyses were simplified without losing accuracy.

Two types of support structures were considered in the case studies: a steel monopile and a concrete gravity-based foundation. Reliability analyses during extreme load events were performed, where the environmental contour method was used to derive the design metocean conditions and the extreme response distributions. Practical applications were demonstrated, including reliability-based design optimization and probabilistic assessment of wave-induced resonant loads. Fatigue reliability analysis and calibration of fatigue partial safety factors, which form a substantial part of this work, were demonstrated for both steel and concrete substructures. The fatigue reliability of a large steel monopile was investigated, accounting for the increased wave-induced fatigue load contribution. For the concrete gravity-based foundation, fatigue reliability was estimated using a fatigue resistance model, which was formulated based on available experimental

concrete fatigue tests.

This thesis presents applications of reliability methods in conceptual and preliminary design stages. Global sensitivity analysis considering both extreme and fatigue design load cases suggested that uncertainties related to environmental parameters (i.e., soil, wind, wave) are generally more significant compared to uncertainties in wind turbine structural parameters. Accounting for the identified important parameters, reliability analyses showed that the currently recommended fatigue design factors (FDF) still satisfy safety requirements for steel monopiles. But as wave load contribution increases due to larger wind turbine or higher water depth, higher FDF values should be recommended. For concrete foundations, it was concluded that fatigue partial safety factors can be reduced without compromising structural safety. The sensitivities of the reliability indices to the stochastic input parameters were also quantified.

Finally, probabilistic frameworks were presented, which can be applied to other foundation concepts. This thesis lays out some fundamental aspects and considerations for practical applications of probabilistic methods in design of offshore wind turbine support structures.

# Resumé


Der er en voksende interesse for anvendelser af probabilistiske metoder til design af havvindmøller. I modsætning til den klassiske, deterministiske designtilgang, har en probabilistisk designtilgang en fordel i at være i stand til at tage hensyn til stedspecifik information, eksperimentelle forsøgsresultater og tilgængelighed af bedre modeller. Dette fører ofte til mere omkostningseffektive designløsninger. For at kunne anvende probabilistisk design i forbindelse med offshore vindmøllestøttekonstruktioner bliver identifikation af de mest betydningsfulde parametre og udvikling af stokastiske modeller nødvendig.

En typisk offshore vindmølle aero-hydro-servo-elastisk beregningsmodel integrerer forskellige submodeller, der repræsenterer metocean miljø, geotekniske forhold, vindmølle kontrol og vindmølle struktur. Dette kræver et stort antal inputparametre, der hver fastlægges med forskellige grader af usikkerhed. Men ikke al usikkerhed er lige vigtig. For et komplekst, ikke-lineært system med et stort antal usikre parametre er der anvendt en global følsomhedsanalyseteknik til at identificere de mest vigtige parametre. Ved at fokusere på de vigtigste parametre blev de efterfølgende pålidelighedsanalyser forenklet uden at miste nøjagtighed.

To typer sub-strukturer blev undersøgt i casestudierne: et stål monopæl fundament og et gravitationsfundament. Pålidelighedsanalyser under ekstreme belastningssituationer blev udført, hvor en konturmetode blev brugt til at fastlægge regningsmæssige metocean-forhold og ekstreme responsfordelinger. Praktiske anvendelser blev demonstreret, inklusive pålidelighedsbaseret designoptimering og probabilistisk vurdering af bølgeinducerede resonansbelastninger. Analyse af pålidelighed mht. udmattelse og kalibrering af partialkoefficienter blev demonstreret for både stål- og betonkonstruktioner. Pålidelighed mht. udmattelse for en stor stålmonopæl blev undersøgt med speciel fokus på den bølge-inducerede udmattelsesbelastning. For beton gravitationsfundamentet blev sikkerheden overfor udmattelse estimeret ved hjælp af en model for udmattelsesstyrken, som blev formuleret baseret på tilgængelige eksperimentelle udmattelsesforsøg for beton.

Denne afhandling præsenterer anvendelser af pålidelighedsmetoder i konceptuelle og foreløbige designstadier. Global følsomhedsanalyser under hensyntagen til både ekstreme og udmattelsesmæssige designbelastningstilfælde antydede, at usikkerheder relateret til miljøparametre (dvs. jord, vind, bølge) generelt er mere signifikante sammenlignet med usikkerheder i vindmøllestrukturparametre. Undersøgelser af de identificerede vigtige parametre viste, at de for tiden anbefalede udmattelsesdesignfaktorer (FDF) opfylder sikkerhedskravene for stålmonopæle. Men når bølgelastningsbidraget stiger på grund af større vindmøller eller større vanddybder, bør højere FDF-værdier anbefales. For beton fundamenter blev det konkluderet, at partialkoefficienter for udmattelse kan reduceres uden at gå på kompromis med den strukturelle sikkerhed. Følsomheden af sikkerhedsindekserne mht. de stokastiske inputparametre blev også kvantificeret.

Endelig blev der præsenteret probabilistiske metoder, som kan anvendes på andre fundaments koncepter. Denne afhandling beskriver nogle grundlæggende aspekter og overvejelser til praktisk anvendelse af probabilistiske metoder ved design af offshore vindmølle fundaments konstruktioner.

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Special thanks is reserved for my friends and family. These are the people who have kept my spirits up throughout this challenging work.

# List of Papers

This Ph.D. thesis follows an article-based format. The first part presents an extended summary of the study. The second part consists of the appended papers.

**Publications included in this thesis:**

- **Paper A:** Velarde, J., Kramhøft, C., & Sørensen, J. D. (2019). Global sensitivity analysis of offshore wind turbine foundation fatigue loads. *Renewable Energy*, 140, 177-189. DOI: 10.1016/j.renene.2019.03.055.
- **Paper B:** Velarde, J., Mankar, A., Kramhøft, C., & Sørensen, J. D. (2019). Uncertainty modelling and fatigue reliability assessment of offshore wind turbine concrete structures. *International Journal of Offshore and Polar Engineering*, 29(2), 165-171. DOI: 10.17736/ijope.2019.il54.
- **Paper C:** Velarde, J., Kramhøft, C., & Sørensen, J. D. (2019). Reliability-based design optimization of offshore wind turbine concrete structures. In *Proceedings of the 13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13, Seoul, South Korea, May 26-30, 2019*.
- **Paper D:** Velarde, J., Vanem, E., Kramhøft, C., & Sørensen, J. D. (2019). Probabilistic analysis of offshore wind turbines under extreme resonant response: Application of environmental contour method. *Applied Ocean Research*, 93, 101947. DOI: 10.1016/j.apor.2019.101947.
- **Paper E:** Velarde, J., Kramhøft, C., Sørensen, J. D., & Zorzi, G. (2019). Fatigue reliability of large monopiles for offshore wind turbines. Submitted to an international journal.
- **Paper F:** Velarde, J., Mankar, A., Kramhøft, C., & Sørensen, J. D. (2019). Probabilistic calibration of fatigue safety factors for offshore wind turbine concrete structures. Submitted to an international journal.

**Other publications:**

- Velarde, J., Kramhøft, C., & Sørensen, J. D. (2018). Uncertainty modeling and fatigue reliability assessment of concrete gravity based foundation for offshore wind turbines. In *Proceedings of the Twenty-eigth (2018) International Ocean and Polar Engineering Conference, ISOPE 2018, Sapporo, Japan, June 10-15, 2018* (pp. 256-264). International Society of Offshore & Polar Engineers.

- Clark, C. E., Velarde, J., & Nielsen, J. S. (2018). Fatigue load reductions in offshore wind turbine monopile foundations in co-located wind-wave arrays. In *Proceedings of the ASME 2018 1st International Offshore Wind Technical Conference, IOWTC 2018, November 4-7, 2018, San Francisco, CA*. American Society of Mechanical Engineers.

- Mankar, Velarde, J., & Sørensen, J. D. (2019). Reliability-based design optimization and inspection planning of wind turbine concrete structures subjected to fatigue. Submitted to *Engineering Structures*.

- Zorzi, G., Mankar, A., Velarde, J., Sørensen, J. D., Arnold, P., & Kirsch, F. (2019). Reliability analysis of offshore wind turbine foundations under lateral cyclic loading. Submitted to *Wind Energy Science*.

# Nomenclature

**Abbreviations**

| | |
|---|---|
| ABS | American Bureau of Shipping |
| ALS | Accidental Limit State |
| API | American Petroleum Institute |
| AWEA | American Wind Energy Association |
| BSH | Bundesamt für Seeschiffahrt und Hydrographie |
| CDF | Cumulative Distribution Function |
| CFD | Computational Fluid Dynamics |
| DFF | Design Fatigue Factor |
| DHI | Dansk Hydraulisk Institut |
| DLC | Design Load Case |
| DNV | Det Norske Veritas |
| DOF | Degree of freedom |
| DTU | Technical University of Denmark |
| FAST | Fatigue, Aerodynamics, Structures and Turbulence |
| FDF | Fatigue Design Factor |
| FE | Finite Element |
| FERUM | Finite Element Reliability Using Matlab |
| fib | Fédération Internationale du Béton |
| FLS | Fatigue Limit State |

| | |
|---|---|
| FLTA | Full Long-Term Approach |
| FORM | First-Order Reliability Method |
| HAWC2 | Horizontal Axis Wind turbine simulation Code 2nd generation |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| IFORM | Inverse First-Order Reliability Method |
| INFRASTAR | Innovation and Networking for Fatigue and Reliability Analysis of Structures - Training for Assessment of Risk |
| ISO | International Standards Organization |
| JCSS | Joint Committee on Structural Safety |
| LPM | Lumped Parameter Model |
| LRFD | Load and Resistance Factor Design |
| NORSOK | Norsk Sokkels Konkuranseposisjon |
| NREL | National Renewable Energy Laboratory |
| NSS | Normal Sea State |
| NTM | Normal Turbulence Model |
| OC3 | Offshore Code Comparison Collaboration |
| OWF | Offshore Wind Farm |
| OWT | Offshore Wind Turbine |
| PDF | Probability Density Function |
| PSD | Power Spectral Density |
| RBDO | Reliability-based Design Optimization |
| SLS | Serviceability Limit State |
| SORM | Second-Order Reliability Method |
| SRC | Standardized Regression Coefficient |
| ULS | Ultimate Limit State |

| | |
|---|---|
| WAMIT | Wave Analysis MIT |

## Greek Symbols

| | |
|---|---|
| $\alpha_i$ | Sensitivity factors $[-]$ |
| $\alpha_{U_w}$ | Wind shear exponent $[-]$ |
| $\beta$ | Reliability index $[-]$ |
| $\beta_t$ | Target reliability index $[-]$ |
| $\Delta$ | Miner's rule model uncertainty $[-]$ |
| $\Delta\beta$ | Annual reliability index $[-]$ |
| $\Delta\sigma$ | Stress cycle amplitude $[MPa]$ |
| $\eta$ | Wave surface elevation $[m]$ |
| $\gamma_m$ | Material partial safety factor $[-]$ |
| $\gamma_S$ | Load partial safety factor $[-]$ |
| $\gamma_{wave}$ | Peak enhancement factor $[-]$ |
| $\Phi(\cdot)$ | Standard normal distribution function $[-]$ |
| $\sigma_1$ | Turbulence standard deviation $[-]$ |
| $\theta_{wave}$ | Wave direction $[deg]$ |
| $\theta_{wind}$ | Wind speed direction $[deg]$ |

## Latin Symbols

| | |
|---|---|
| $A$ | Weibull scale parameter $[m/s]$ |
| $D_f$ | Total fatigue damage $[-]$ |
| $f$ | Sea state occurrence frequency $[-]$ |
| $f_n$ | OWT natural frequency $[Hz]$ |
| $H_s$ | Significant wave height $[m]$ |
| $k$ | Weibull shape parameter $[-]$ |
| $M_x$ | Bending moment along major x-axis $[MNm]$ |

| | |
|---|---|
| $N_F$ | Number of failures $[-]$ |
| $N_{MC}$ | Number of Monte Carlo simulations $[-]$ |
| $P_F$ | Probability of failure $[-]$ |
| $q$ | Annual probability of exceedance $[-]$ |
| $R_c$ | Normalized characteristic resistance $[-]$ |
| $R_d$ | Normalized design resistance $[-]$ |
| $S_c$ | Normalized characteristic load $[-]$ |
| $S_d$ | Normalized design load $[-]$ |
| $S_{max}$ | Maximum stress of a stress cycle $[MPa]$ |
| $S_{min}$ | Minimum stress of a stress cycle $[MPa]$ |
| $T_p$ | Wave peak period $[s]$ |
| $T_R$ | Return period $[years]$ |
| $TI$ | Turbulence Intensity $[-]$ |
| $u^*$ | Design point at standard normal space $[-]$ |
| $U_c$ | Current velocity $[m/s]$ |
| $U_{hub}$ | Mean wind speed at hub height $[m/s]$ |
| $U_{in}$ | Wind turbine cut-in wind speed $[m/s]$ |
| $U_{out}$ | Wind turbine cut-out wind speed $[m/s]$ |
| $U_w$ | Mean wind speed at reference height $[m/s]$ |
| $X_m$ | Concrete fatigue damage model uncertainty $[-]$ |
| $X_{dyn}$ | Dynamic model uncertainty $[-]$ |
| $X_{SCF}$ | Stress concentration factor uncertainty $[-]$ |
| $X_{wave}$ | Wave load model uncertainty $[-]$ |

# Contents

# Chapter 1

# Introduction

## 1.1 Motivation

The world's first offshore wind farm was built in *Vindeby*, Denmark in 1991. Since then, the offshore wind energy industry has achieved substantial technological developments and energy cost reductions. According to the *Offshore Wind Energy Oulook* published by International Energy Agency (2019), the global offshore wind power capacity is expected to increase 15-fold in the next two decades. Now established as a mature technology, offshore wind is set to play a valuable role in navigating clean energy transition and in achieving renewable energy targets.

The offshore wind industry needs continuous technological advancements that covers the whole supply chain in order to increase competitiveness against traditional energy sources. Foundations for offshore wind turbines (OWTs), which account for about 20-25% of the total project cost (IEA, 2019), are still confronted with site-specific design challenges. Opportunities exist towards streamlining of the design process, optimization of exisiting design concepts and development of new foundation solutions.

The general types of bottom-fixed foundations mostly used today are illustrated in Fig. 1.1. Accounting for about 80% of the total installations at the end of 2018, monopiles remain the preferred foundation solution (WindEurope, 2019). This is followed by jacket and gravity-based foundations at 8% and 6%, respectively.

The design and analysis of OWT support structures, both in ultimate limit state (ULS) and fatigue limit state (FLS), are currently based on semi-probabilistic approach, where partial safety factors are applied to account for uncertainties in the load and resistance models. In order to arrive at cost-effective foundation solutions, optimization and continuous

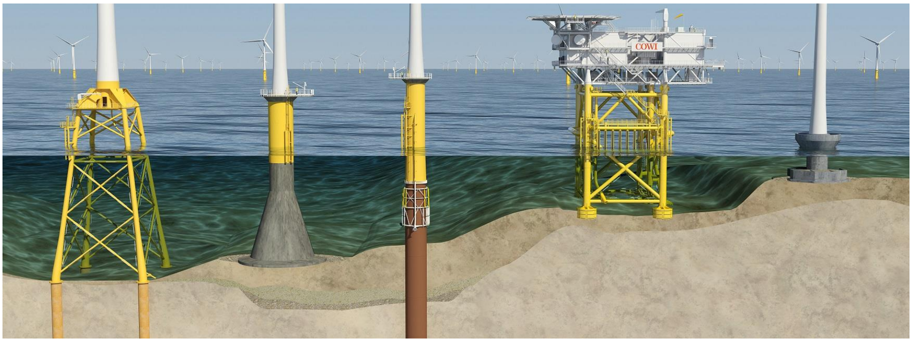


**Fig. 1.1:** General types of bottom-fixed OWT foundations © COWI

updating of structural design codes become necessary. This ensures that new design uncertainties introduced (e.g. due to bigger OWTs and deep water installations) are taken into account.

A probabilistic design approach is recognized as an alternative to the traditional semi-probabilistic design approach. A main advantage is the possibility of directly accounting for site-specific uncertainties, which can potentially improve design optimization. Furthermore, applications of reliability methods can address critical design conditions which are yet to be covered by design code specifications, and address modification of partial safety factors when better models or more information are available. This Ph.D. thesis focuses on probabilistic design and analysis of OWT support structures.

## 1.2 Aim and Scope

The aim of this Ph.D. thesis is to demonstrate applications of probabilistic methods to design and analysis of offshore wind turbine support structures. Emphasis is given to assessment of fatigue damage accummulation of both steel and concrete structural elements, while taking into account the relevant sources of uncertainties. The primary aim is to optimize the design of support structures without compromising structural safety.

The specific research objectives are::

- to perform a global sensitivity analysis of an integrated offshore wind turbine aeroelastic model considering the relevant sources of uncertainties
- to demonstrate reliability-based design optimization (RBDO) of offshore wind turbine foundations considering ULS and FLS

- to assess the structural safety of wave-sensitive offshore wind turbines against extreme resonant responses
- to investigate fatigue reliability and calibrate fatigue safety factors for large steel monopiles and concrete gravity-based foundations

This study deals with the primary sources of uncertainties related to the environmental conditions, the OWT load model and the material resistance model. Fig. 1.2 illustrates the uncertainties in reliability assessment of OWT support structures. A multidisciplinary approach covering wind turbine technology, offshore engineering and reliability engineering is essential to address the identified challenges.

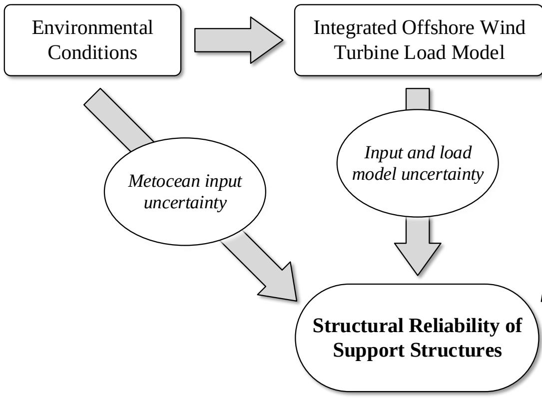



**Fig. 1.2:** Primary sources of uncertainties in reliability assessment of offshore wind turbine support structures

Offshore wind turbine loads are calculated based on time-domain, fully-coupled, aero-hydro-servo-elastic simulation tool. The main focus in this PhD work is on the probabilistic design and reliability aspects, and not on hydrodynamic loads, which are estimated based on linear wave theory. Results are therefore limited to preliminary design. No detailed finite element analysis is performed in this study.

## 1.3 Publications

An overview of the different research areas covered by the appended papers is shown in Fig. 1.3. These six peer-reviewed publications address the research objectives outlined above. By focusing on the relevant sources of uncertainties established in papers A and B, the rest of the publications can be rationally simplified without losing accuracy. Papers C and D applied reliability methods to extreme response analysis, while papers E and F focused on fatigue reliability of OWT support structures.

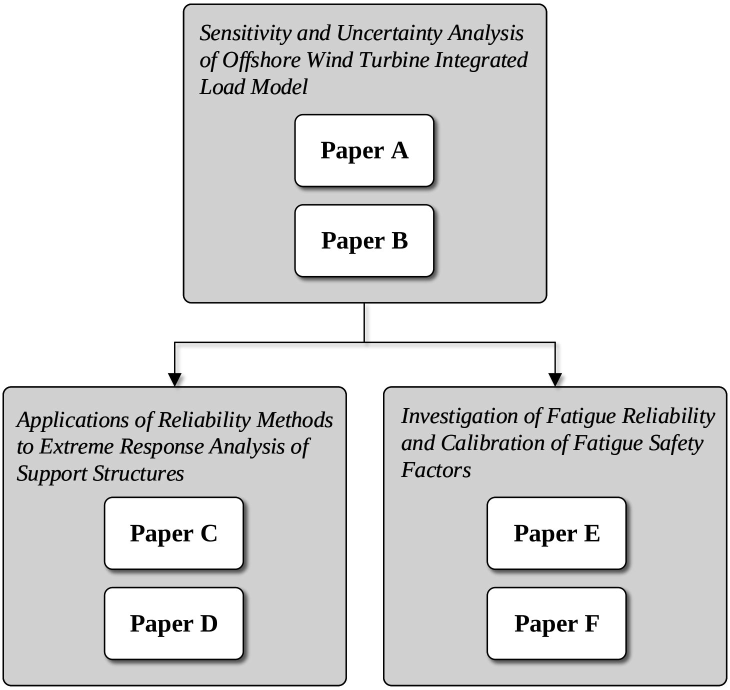



**Fig. 1.3:** Overview of research areas and related scientific publications

**Paper A** investigates the sensitivity of OWT fatigue loads with respect to the structural, geotechnical, and metocean input parameters. Based on two global sensitivity analysis techniques, the most significant input parameters were identified for various design load cases. The accuracy of aeroelastic load calculations can be further improved by focusing on a smaller set of parameters that governs the uncertainties.

**Paper B** examines the propagation of uncertainties in fatigue assessment of concrete GBF. Based on S-N approach, concrete fatigue damage accummulation models are formulated. It is concluded that the fatigue resistance model uncertainty, which is calibrated against available experimental concrete fatigue tests, governs the total uncertainty in fatigue assessment of OWT concrete structures.

**Paper C** demonstrates reliability-based design optimization (RBDO) in a concrete GBF, where an optimal combination of prestressing steel and reinforcements is found. In addition, application of environmental contour method in deriving OWT extreme load distribution is presented. RBDO results in an optimal design, which satisfies the required reliability level at the minimum cost.

**Paper D** introduces a probabilistic framework for assessment of OWT extreme loads due to wave-induced resonant responses. Based on in-situ metocean observations, environmental contour method is used to define the design conditions. This work addresses the lack of design specifications for assessment of resonant loads, which can potentially govern the design of large monopiles.

**Paper E** investigates the fatigue reliability of wave-sensitive, large monopiles supporting a 10 MW OWT. The objective is to reflect changes in the load characteristics, particlarly the increase in wave load contribution, to fatigue design rules. Based on S-N approach, reliability-based calibration of fatigue design factors (FDF) is performed considering a critial welded steel detail.

**Paper F** investigates current fatigue design rules for offshore wind turbine concrete structures. When better models or more information are available, partial safety factors can be modified according to the appropriate target reliability levels. Relative to steel, the uncertainty in concrete fatigue resistance models is generally higher. Based on available experimental fatigue tests, a fatigue reliability model for concrete is formulated and applied in two numerical examples. This work indicates that the currently recommended material partial safety factor can be reduced without compromising structural safety.

The remianing part of this thesis is outlined as follows. **Chapter 2** summarizes the related literature on OWT load calculations, which also describes the state-of-the-art and the knowledge gaps in the research area. **Chapter 3** discusses the current OWT fatigue design rules. This is followed by **Chapter 4**, which provides a discussion of reliability methods and its specific applications to design and analysis of OWTs. Lastly, **Chapter 5** summarizes the main scientific contributions of this thesis and provides recommendations for future work.

# Chapter 2

# Offshore Wind Turbine Load Analysis

## 2.1 Integrated Load Simulations

The design of an offshore wind turbine is traditionally based on an iterative procedure. Detailed aeroelatic simulations are performed, mostly by the wind turbine manufacturer, with focus on the wind turbine itself, while the support structure and wave loads are represented by crude models; and detailed structural analysis of the substructure is performed with a crude wind turbine model. Seidel (2010) described a typical commercial interfaces between project stakeholders involved in the design of an OWT support structure. The ideal approach is an intergrated approach, where both detailed wind turbine and support structure models are fully-coupled.

The structural analysis of an OWT is an integrated process, where the complex interaction between the soil, support structure, hydrodynamic loads, aerodynamic loads and wind turbine control must be taken into account. Fig. 2.1 shows an overview of an offshore wind turbine and its significant interaction with the environment. Note that electrical components, wind turbine control, scour protection and wake interactions with other OWTs are not depicted in the figure.

Several research and commercial aero-servo-hydro-elastic codes are under constant development to promote innovations and satisfy industry requirements. The most widely used numerical tools include *FAST (Fatigue, Aerodynamics, Structures and Turbulence)* developed by NREL (J. M. Jonkman, Buhl Jr, et al., 2005), *HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) developed by DTU–Risø* (Larsen & Hansen, 2015), and *Bladed* developed by DNV GL (2014a). An overview of available simulation tools

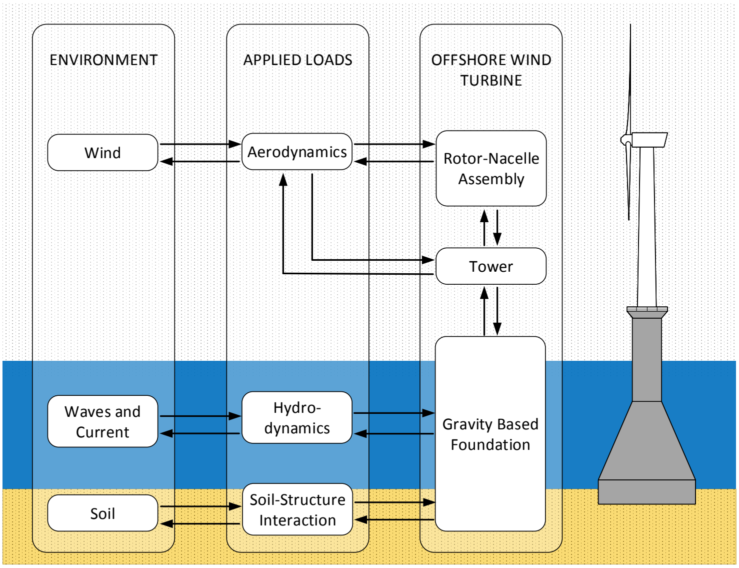



**Fig. 2.1:** Interaction between wind loads, wave loads, soil and an offshore wind turbine (Velarde, Kramhøft, & Sørensen, 2019a)

and modeling capabilities are described by Passon and Kühn (2005), Cordle, Jonkman, et al. (2011), and Vorpahl, Schwarze, Fischer, Seidel, and Jonkman (2013).

The verification of aeroelastic simulation tools, which vary in sophistication and structure, is of equal importance as its development. The *Offshore Code Comparison Collaboration* (OC3) study (J. Jonkman & Musial, 2010) of the IEA was executed, which allows participating universities, research institutes and industries to compare simulation results and identify sources of differences. The OC3 focused on design benchmarks for a monopile, a tripod and a floating spar-buoy on a deep water. Following this study, the OC4 *(Offshore Code Comparison Collaboration Continuation)* (Popko et al., 2012; A. Robertson et al., 2014) was conducted to compare simulations for both jacket and floating semisubmersible foundations. Lastly, the OC5 *(Offshore Code Comparison Collaboration, Continued, with Correlation)* (A. N. Robertson et al., 2016) was conducted to validate results from OC3 and OC4 to experimental test data. Based on these results, the validity of various modeling assumptions can be assessed, which enables further development in OWT load analysis.

Lastly, the pioneering works of Kühn (2001) and Van Der Tempel (2006) on OWT structural dynamics have led to the development of design methodologies currently applied today. More recent studies focusing on probabilistic design of wind turbines include the Ph.D. works of H. F. Veldkamp (2006), Toft (2010), Dong (2012), Wandji (2017), Horn (2018), and C. J. Hübler (2019).

## 2.2 Structural Modeling

The three structural analysis methods commonly used in wind turbine simulation tools include (1) finite element (FE), (2) modal approaches and (3) multi-body systems (MBS) (Passon & Kühn, 2005). In the FE approach, the wind turbine components are discretized into finite beam elements based on Euler-Bernoulli or Timoshenko beam theories, with the latter accounting for shear deformations. Linear FE approximations are usually applied, which are associated with large number of degrees of freedom (DOF). Although computationally expensive, FE modeling has fewer geometric restrictions and can effectively model lattice structures. In the modal approach, the deflections are calculated from superposition of relatively low number of eigenmodes. This makes the calculation very efficient, in exchange of some limitations such as low number of DOFs and linear assumption. The MBS approach features finite set of elements coupled by elastic hinges. It combines the advantage of both modal and FE approaches by retaining a small number of DOFs while at the same time allows modeling of nonlinearities (Passon & Kühn, 2005). The modal and MBS approaches allow wind turbine load analysis at lower computational cost, which makes it a popular choice for structural modeling. At the time of writing, *FAST* (J. M. Jonkman et al., 2005) and *Bladed* (DNV GL, 2014a) implement a combined modal and MBS formulation, while *HAWC2* (Larsen & Hansen, 2015) is based on MBS formulation where each body is an assembly of Timoshenko beam elements.

## 2.3 Hydrodynamics

To understand the nature of hydrodynamic loads and to address related challenges, knowledge on wave theory, ocean physics and wave-body interaction are necessary. Popular modeling approaches include the use of linear wave theory, potential flow theory and computational fluid dynamics (CFD) (Benitz, Lackner, & Schmidt, 2015).

The linear wave theory, also called Airy wave theory, is a widely used formulation due to its simplicity. It describes wave particle kinematics based on simplified potential flow theory and is valid for small-amplitude waves in deep water (Vorpahl et al., 2013). For shallow water depths, waves become steeper and the effect of nonlinearitites becomes more significant. Based on their validity evaluated in terms of water depth and sea state, different wave theories are recommended by the API (1989), including the stream function theory developed by Dean and Dalrymple (1991) as widely applicable for modeling shallow water waves.

A comparison between linear and fully nonlinear wave model showed that the linear wave model significantly underestimates fatigue loads, particularly when the wind turbine is in parked condition (Marino, Giusti, & Manuel, 2017). The effect of fully nonlinear irregular waves on fatigue life of a monopile was also investigated by Schløer et al. (2012), where analysis suggests that wave nonlinearity can influence the wave-induced fatigue damage significantly. The study also investigated possibilities of springing and ringing phenomena, which are dynamic excitations caused by nonlinear higher order waves. Springing responses can be excited when the natural frequency is about twice the wave frequency. Ringing responses, on the other hand, are characterized by resonant build-up of vibrations that can be excited when the natural frequency is about four times the wave frequency. It was investigated by Grue and Huseby (2002) on a vertical cylinder. In 1950, Morison et al. (1950) developed an empirical equation, now commonly referred to as Morison's equation, for calculating wave forces on slender offshore structures as the sum of drag and inertia forces.

For non-slender bottom-fixed foundations, such as large monopiles and GBFs, the Morsion's equation becomes inaccurate due to increasing significance of diffraction. Diffraction accounts for the effect of scattering waves upon impact with an impermeable body and generally reduces wave loads on the structure (Benitz et al., 2015). For simple shapes, such as circular piles, MacCamy and Fuchs (1954) developed a theory which can be applied with Morison's equation to account for diffraction. Bachynski and Ormberg (2015) demonstrated that accounting for diffraction using MacCamy-Fuchs theory, particularly for lower sea states with short periods, has a significant effect on the fatigue lifetime of large-diameter monopiles. A comparison between three different wave load calculation methods: Morison, diffraction and pressure integration method, was done by Camp et al. (2003) for both shallow water and deep water GBF. Results show that Morison method is the least accurate, while pressure integration method (also called Froude-Krylov method) gave the least error. CFD-based methods could provide more accurate load predictions at the expense of higher computational times.

Although CFD methods are computationally expensive, its applications for hydrodynamic modeling of both bottom-fixed and floating OWT foundations have increased (Benitz et al., 2015). CFD-based calculations are more suitable for analysis of short time series, such as wave run-up and wave breaking phenomena. Extreme wave forces and wave run-up on monopiles were investigated by E. D. Christensen, Bredmose, and Hansen (2005), Bredmose and Jacobsen (2010) and Peng, Wellens, and Raaijmakers

(2012). Applications of CFD method for floating OWT foundations were also demonstrated in several literature (Beyer et al., 2013; Quallen et al., 2013; Tran, Kim, & Song, 2014). For a GBF, a study by Bredmose et al. (2006) focused on numerical reproduction of extreme wave loads on a GBF based on model tests conducted at DHI wave basin in Denmark. Comparison with loads estimated using Morison's equation shows that the simpler approach can reproduce the general trend of wave load history, but not the extreme moment. E. D. Christensen et al. (2011) also applied CFD method to investigate uncertainties in irregular wave breaking loads on a GBF installed in a shallow water, where wave breaking occurs. The GBF design on Thornton bank offshore wind farm in Belgium was used as the reference design for this study. The application of CFD-based wave loads in aeroelastic simulations was demonstrated by Schløer, Paulsen, and Bredmose (2014), where comparison between potential flow-based and CFD-based wave loads for low and high sea states was presented.

In addition to linear waves and stream function waves implemented in the code, *HAWC2* is also capable of deriving potential flow solution via interface with *WAMIT* (C.-H. Lee, 1995). The *HAWC2-WAMIT* coupling is described by Hansen (2014), and its applications to large floating wind and wave energy platform and offshore wind turbine platform were demonstrated by Yde et al. (2015) and Borg, Hansen, and Bredmose (2016), respectively.

Research and commercial simulation tools have different approaches in modeling hydrodynamic loads. Most tools implement linear wave theory combined with Morison's equation for wave load calculation, although some tools allow options for other wave load models, such as higher order wave loads and potential flow-based solutions. The IEC (2009) provides recommendations on the selection of regular wave theory as a function of normalized water depth $(d/gT^2)$ and nornmalized wave height $(H/gT^2)$ as shown in Fig. 2.2. For most fatigue-related sea states at intermediate to deep water conditions, the linear wave theory provides acceptable load estimates.

As the offshore wind industry pushes to larger wind turbines and higher water depths, larger bottom-fixed structures more sensitive to wave loading are expected. In addition to the challenges related to hydrodynamic load modeling, changes in the loading characteristics and the model uncertainties must be reflected in the relevant design codes.

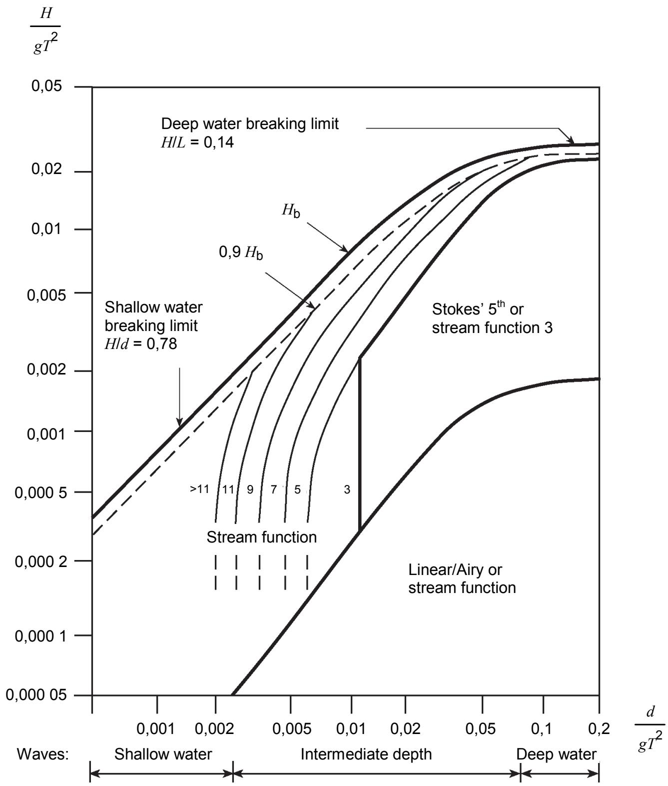



**Fig. 2.2:** Selection of suitable wave theory as a function of normalized water depth $(d/gT^2)$ and normalized wave height $(H/gT^2)$ (International Electrotechnical Commission, 2009)

## 2.4 Soil-Structure Interaction

The interaction between the soil and foundation greatly influences both the static and dynamic response of an offshore wind turbine. It follows that having a more accurate foundation model leads to a more accurate fatigue load prediction.

Several investigations have been done to assess the accuracy of current modeling techniques, particularly on monopiles, the most common type of foundation for intermediate water depths. Bush and Manuel (2010) compared different foundation modeling approaches and found that assuming a rigidly fixed foundation generally underestimates loads compared to adopting a flexible foundation model. Bhattacharya and Adhikari (2011) represented a flexible monopile foundation using translational and rotational springs. The results, validated through experimental model tests, showed that the natural frequency and damping factors are highly sensitive to the foundation stiffness. In modeling soil-monopile interaction, the current practice follows the *p-y method* or *API method* (API, 1989). The method is a Winkler-type approach, which employs uncoupled nonlinear springs represented by p-y curves to support the monopile along the embedded length. Koukoura et al. (2013) used the *API method* to model a monopile foundation and validated the model using strain measurements in Walney Offshore Wind Farm 1. Discrepancies between simulation results and measured quantities exist, which were attributed to differences in rotor design of the actual wind turbine, wind turbulence assumptions and uncertainties related to the foundation model. Since the *API method* is based on testing of two identical steel piles with diameters of approximately 2 meters (or less), the method may not be accurate for large-diameter monopiles due to the associated rigid pile behaviour (Krolis, van der Zwaag, & de Vries, 2010). A study on FE modeling of large diameter piles by Lesny and Wiemann (2006) also showed that the API method tends to overestimate soil stiffness for large diameter piles, particularly at greater soil depths. Other shortcomings of the *API method* are exclusion of hysteretic and radiation damping, slippage and gapping at the soil-pile interface, and effects of stress history as outlined by Van Buren and Muskulus (2012).

Most aeroelastic simulation tools represent soil-structure interaction by modifying the boundary condition as illustrated in Fig. 2.3. These foundation models do not account for other nonlinear effects, such as cyclic degradation and permanent deformations. While FE programs are capable of implementing nonlinear constitutive laws, its implementation or coupling with aeroelastic tools is rarely done due to very high computational expense. Current industry practice involves the use of FE models to derive soil springs. This is illustrated in Fig. 2.4, where a 3D FE model of a monopile is used to derive distributed springs or p-y curves.

For a more practical approach, modeling of foundations using macro-elements has been introduced by Nova and Montrasio (1991) to model settlements of shallow foundations on sand. The use of macro-elements allow representation of constitutive laws in terms of parameters determined from simple calibration tests. Further modifications of macro-element formulation for shallow foundations has been done to improve plasticity models (Chatzigogos, Pecker, & Salencon, 2009), to account for cyclic responses (Salciarini & Tamagnini, 2009) and to extend application to bucket foundations (Foglia et al., 2014) and GBF (Philippe et al., 2013). Macro-element foundation models have also been integrated with time-domain aeroelastic tools, as demonstrated in several literature (Page et al., 2018; Skau et al., 2018). An alternative to macroelements is the use of lumped-parameter models (LPM), which only adds a few degrees of

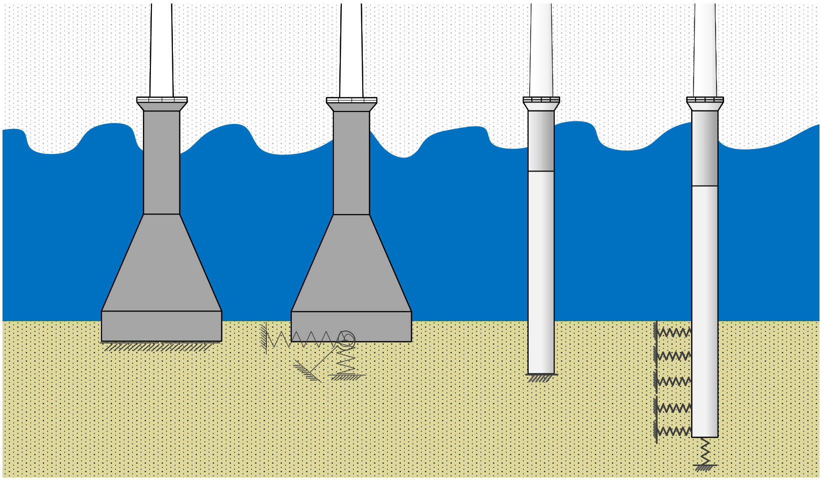


**Fig. 2.3:** Typical representations of soil-structure interaction in integrated aeroelastic models. From left to right: fixed base, coupled springs, apparent fixity model, distributed springs.

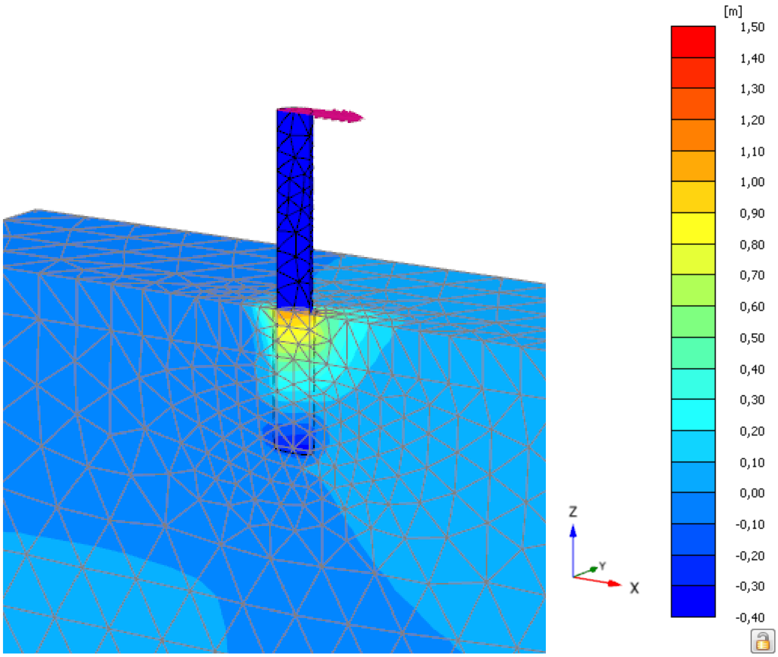



**Fig. 2.4:** Finite element modeling of soil-structure interaction in PLAXIS 3D. Adapted from Velarde et al. (2019).

freedom to represent dynamic soil-structure interaction. The efficiency of LPM and its coupling with an aeroelastic code has been demonstrated on a gravity footing (Andersen & Liingaard, 2007) and bucket foundation (Andersen, Ibsen, & Liingaard, 2009). Although LPMs are more efficient than macroelements, limitations exist, such as accuracy being limited to certain frequency and the model's failure to account for a cyclic degradation and permanent soil deformations.

Modeling of soil-structure interaction in aeroelastic simulations is normally simplified to reduce calculation time. For a chosen soil-structure interaction model, the associated model uncertainties should be considered in the design process. It is often interesting to know which of the several sources of uncertainties govern the uncertainty in the OWT response.

## 2.5 Sensitivity Analysis

Sensitivity analysis can be defined as the study of how the uncertainty in the model output can be allocated to different sources of uncertainy in the model input (Saltelli, Tarantola, Campolongo, & Ratto, 2004). The most simple and most common approach is referred to as the *one-factor-at-a-time* approach, where the change in output is assessed considering incremental changes in one input parameter. However, this local approach can overlook critical regions of the input space and lead to invalid conclusions, particularly when considering nonlinear numerical models with a large number of uncertain input parameters. Alternatively, global sensitivity analysis methods are effective tools that are applicable to models with a large number of input parameters. Established methods of this type include Elementary Effects method or Morris Screening (Morris, 1991), Monte Carlo and linear regression (Helton & Davis, 2003) and variance-based methods (Saltelli et al., 2008).

Integrated numerical models for OWTs require a considerable number of input parameters. Sensitivity analyes have been performed in the field of offshore wind energy, mostly considering a particular aspect related to either soil-foundation interaction, hydrodynamic load model, aerodynamic load model, wind turbine control, environmental conditions or a combination of a few. Several papers (Carswell, Arwade, DeGroot, & Lackner, 2015; Damgaard, Andersen, Ibsen, Toft, & Sørensen, 2015; Haldar & Babu, 2008; Vahdatirad, Andersen, Ibsen, Clausen, & Sørensen, 2013; Zaaijer, 2006) have investigated soil spatial variability on structural response. Results indicate that variation in soil characteristics has a great influence on structural reliability. Papers (Murcia et al., 2018; Toft, Svenningsen, Moser, Sørensen, & Thøgersen, 2016; Toft, Svenningsen, Sørensen, Moser, & Thøgersen, 2016) that focused on the assessment of wind climate uncertainty showed that turbulence intensity governs the variation in fatigue loads of onshore wind turbines. In addition, it was found that 10-30% of the uncertainties in reliability of wind turbine components is governed by wind parameter uncertainties. Lastly, a global sensitivity analysis considering uncertainties related to soil, wind, wave and structural models was demonstrated by C. Hübler, Gebhardt, and Rolfes (2017) for both monopile and jacket support structure. The results indicate that only a few parameters are important, and that OWT numerical models can be simplified by deterministic representation of less significant input parameters. The crude Monte Carlo method remains the most common global sensitivity analysis method due to simplicity of the procedure. The Monte Carlo method can also be applied to probabilistic fatigue design of foundations, as demonstrated by Müller and Cheng (2018). Other methods, such as Elementary Effects method have also been demonstrated in several papers (Martin, Lazakis, Barbouchi, & Johanning, 2016; Ziegler & Muskulus, 2016), covering subject areas related to offshore wind farm operation, maintenance and lifetime extension.

Identification of the most important sources of uncertainties in a numerical model offers a number of advantages. The results facilitate identification of important regions in the input space, which could drive research direction (Saltelli et al., 2008). In addition, numerical models can be simplified (i.e., assume a fixed value for non-significant parameters) and more attention can be given to assessment of few important parameters that govern the model output.

**Paper A** of this thesis demonstrated two global sensitivity analysis methods in an OWT numerical load model. Similarly, **Paper B** also looked into fatigue of OWTs, but included fatigue resistance model uncertainty in the analysis.

# Chapter 3

# Offshore Wind Turbine Fatigue Design

## 3.1 Design Standards

Several design standards and guidelines cover the design and analysis of offshore wind turbines. A list of relevant and recognized guidelines is summarized in Table 3.1. The DNVGL-ST-0126 (2018b) standard for *Support structures for wind turbines* superseded the DNV-OS-J101 (2014) standard for *Design of offshore wind turbine structures*. Both documents summarize the design principles and design requirements, and are intented to be used with the other relevant standards.

Guidelines for the assessment of external conditions for offshore wind turbine sites are primarily covered by IEC 61400-1 (2005, 2019a), IEC 61400-3 (2009, 2019b) and DNVGL-RP-C205 (2014b). In relation to external conditions, the design has to fulfill requirements related to both fatigue and to extreme loads. The IEC 61400-3 (2009) and DNVGL-ST-0437 (2016b) outline design situations and load cases for assessment of fatigue limit states (FLS), ultimate limit states (ULS) and serviceability limit states (SLS). Design situations for both ULS and FLS analyses include normal power production, occurrence of wind turbine fault, wind turbine start-up, emergency shutdown, parked conditions, and situations related to transport, assembly and maintenance.

For fatigue verification of steel and concrete structures, most standards (including DNVGL-RP-C203 and DNVGL-ST-C502) recognize the application of the cumulative linear damage theory according to Palmgren-Miner rule. A more detailed discussion is presented in the following sections. Other alternative guidelines for detailed structural design of steel and concrete structures, as shown in the non-exhaustive list summarized in Table 3.1, are also recognized by different classification societies.

**Table 3.1:** Relevant design standards and guidelines for OWT support structure design

| Document code | Title |
|---|---|
| ABS Standard | *Bottom-founded offshore wind turbine installations* |
| API RP 2A-WSD | *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design* |
| AWEA OCRP | *Recommended Practices for Design, Deployment, and Operation of Offshore Wind Turbines in the United States* |
| BSH Standard | *Design of Offshore Wind Turbines* |
| DNVGL-RP-C203 | *Fatigue design of Offshore Steel Structures* |
| DNVGL-RP-C205 | *Environmental conditions and environmental loads* |
| DNVGL-ST-0126 | *Support structures for wind turbines* |
| DNVGL-ST-0437 | *Loads and site conditions for wind turbines* |
| DNVGL-ST-C502 | *Offshore Concrete Structures* |
| EN 1992 | *Eurocode 2: Design of concrete structures* |
| EN 1993 | *Eurocode 3: Design of steel structures* |
| EN 10025 | *Hot rolled products of structural steels* |
| IEC 61400-1 | *Wind Turbines - Part 1: Design Requirements* |
| IEC 61400-3 | *Wind Turbines - Part 3: Design Requirements for Offshore Wind Turbines* |
| fib Model Code | *fib Model Code for Concrete Structures 2010* |
| NORSOK N-004 | *Design of Steel Structures* |

## 3.2 Fatigue Damage Assessment

Fatigue assessment of an offshore wind turbine substructure is normally performed by the procedure is illustrated in Fig. 3.1. This procedure can be divided into the following tasks:

1. Preparation of the **metocean design basis**
2. Development of an **integrated OWT model**
3. Performing **time-domian analyses** considering all relevant fatigue DLCs and their corresponding occurrence probabilities
4. **Postprocessing** of simulation results (e.g., rainflow counting to determine number of stress cycles)
5. Fatigue damage calculation based on the **S-N approach**
6. Assessment of the total fatigue damage based on **linear damage accummulation** theory

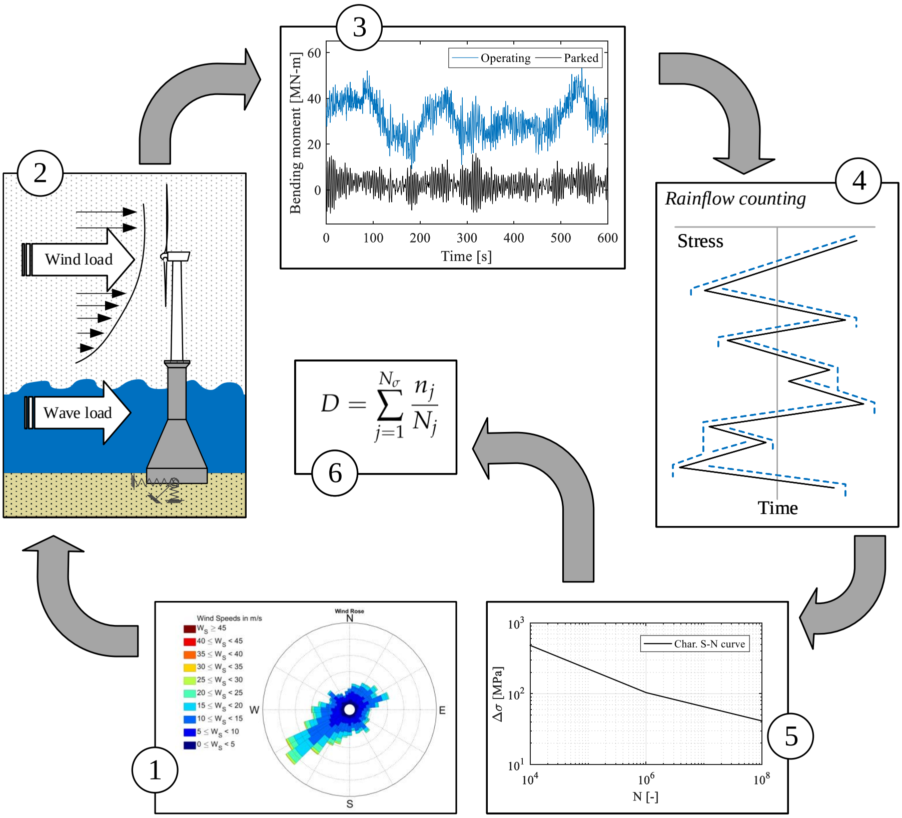



**Fig. 3.1:** Procedure for fatigue design of OWT substructures based on S-N approach

In current industry practice, steps 2 and 3 outlined above can involve the application of superelements in integrated simulation tools (e.g., Bladed, HAWC2, Flex5). Superelements, which are normally provided by the foundation designer to the wind turbune supplier, allow reduced representation of the foundation structural properties and hydrodynamic loads. The calculated load-time histories in the integrated model are applied back to a more detailed FE model of the foundation designer, normally at the tower-foundation interface. This approach is particularly more relevant for more complex structures, such as jacket foundations, where more detailed structural and hydrodynamic models are necessary.

## 3.3 Metocean Design Basis

Before fatigue assessment can be performed, the site-specific metocean design basis has to be established. Fig. 3.2 illustrates the required metocean data, which includes the mean wind speed ($U_w$), significant wave height ($H_s$), wave peak period ($T_p$), and mean wind ($\theta_{wind}$) and wave ($\theta_{wave}$) direction. As outlined in both IEC 61400-3-1 (2019b) and DNVGL-ST-0437 (2016b), the joint probability distribution of $U_w$, $H_s$ and $T_p$ has to be considered in fatigue DLCs. This is in addition to the use of characteristic (conservative) values of other climatic parameters (e.g., 90% quantile of the turbulence intensity). Moreover, analysis considering the wind and wave directionality should be considered.

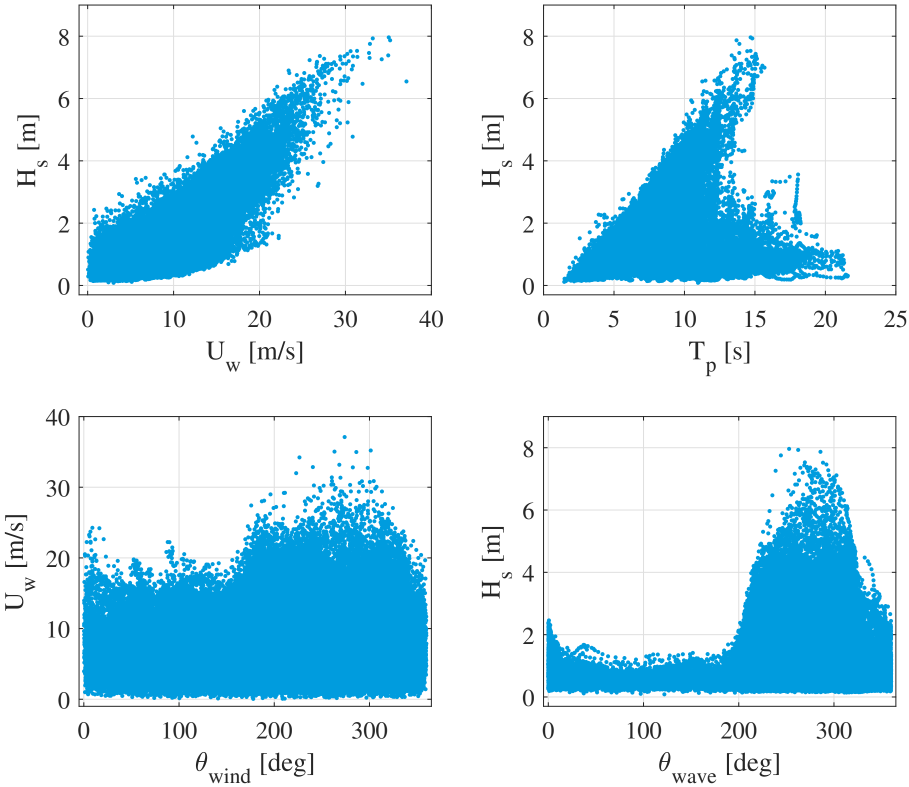



**Fig. 3.2:** Illustration of necesary metocean data for fatigue assessment of OWTs. Hindcast data is from *Vesterhav Nord* OWF.

For fatigue simulations, wave kinematics are generated assuming *normal sea states* (NSS). The expected values of $H_s$, $T_p$ and $\theta_{wave}$ are conditional to the

10-minute mean wind speeds. For the wind conditions, the *normal turbulence model* (NTM) is recommended by the IEC (2005). In NTM, the turbulence standard deviation $(\sigma_1)$ corresponds to the 90% quantile for the given $U_{hub}$. This recommendation provides the safety margin for the estimation of fatigue loads, under the assumption that the variation in turbulence intensity $(TI)$ governs the fatigue loads.

Based on the joint wind and wave distribution, a number of representative environmental conditions for fatigue analysis are established. This reduction is most commonly referred to as the *lumped scatter diagram*. The sea states are traditionally binned according to the $U_w$, which normally follows a Weibull distribution as illustrated in Fig. 3.3. The mean wind speed at a reference height (usually 10 m) are usually extrapolated to the predetermined hub height (90 to 120 m), which depends on the site and wind turbine capacity. Consequently, the probabilities of occurrence $(f)$ for each sea state are estimated based on the wind speed distribution. Table 3.2 summarizes a lumped scatter diagram, which are derived based on hindcast data. $\gamma_{wave}$ refers to the peak enhancement factor, a parameter for defining the wave spectrum.

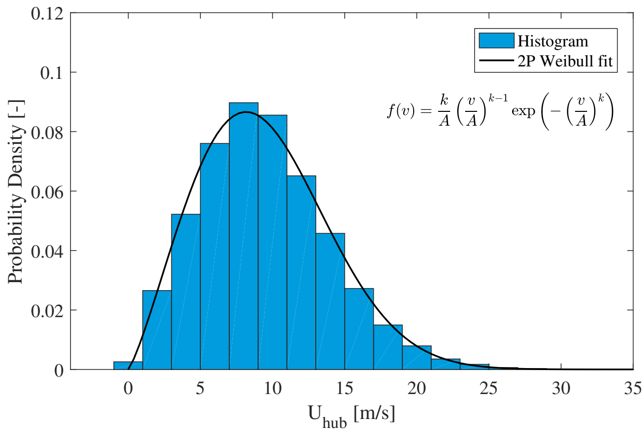



**Fig. 3.3:** Wind speed $(v)$ distribution and Weibull fit $(A = 10.67\ m/s,\ k = 2.23)$ using hindcast data from *Vesterhav Nord* OWF. Adapted from Velarde et al. (2019).

Other parameters, such as wind shear exponent $(\alpha_{U_w})$ and current velocity $(U_c)$, are also considered in practice. It is noted that industry practice requires simulations considering directional variation (normally 30 degree sectors are used) and the $T_p$ range distribution. For a reference design basis, the *UpWind project* (Fischer, De Vries, & Schmidt, 2010) provided a list of the necessary metocean parameters for both shallow and deep water sites in the North Sea.

**Table 3.2:** Lumped scatter diagram at *Vesterhav Nord* OWF based on hindcast data (wind speed direction: 0-360 deg). Adapted from Velarde et al. (2019).

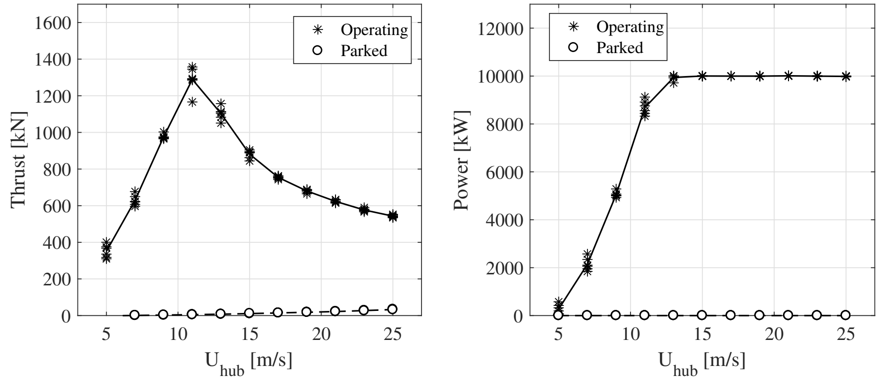
| Sea state | $U_{hub}$ range $[m/s]$ | $U_{hub}$ $[m/s]$ | $f$ [-] | Mean $H_s$ $[m]$ | Mean $T_p$ $[s]$ | $\gamma_{wave}$ [-] |
|---|---|---|---|---|---|---|
| 1 | 4-6 | 5 | 0.053 | 0.82 | 6.8 | 1.0 |
| 2 | 6-8 | 7 | 0.104 | 1.01 | 7.0 | 1.0 |
| 3 | 8-10 | 9 | 0.152 | 1.24 | 7.1 | 1.0 |
| 4 | 10-12 | 11 | 0.179 | 1.55 | 7.4 | 1.0 |
| 5 | 12-14 | 13 | 0.171 | 2.01 | 7.8 | 1.0 |
| 6 | 14-16 | 15 | 0.130 | 2.53 | 8.2 | 1.0 |
| 7 | 16-18 | 17 | 0.092 | 3.07 | 8.9 | 1.0 |
| 8 | 18-20 | 19 | 0.055 | 3.65 | 9.9 | 1.0 |
| 9 | 20-22 | 21 | 0.030 | 4.08 | 10.4 | 1.0 |
| 10 | 22-24 | 23 | 0.016 | 4.76 | 11.4 | 1.0 |
| 11 | 24-26 | 25 | 0.007 | 5.40 | 12.9 | 1.0 |
| - | >26 | - | <0.01 | - | - | - |
| Sum | | | 0.99 | | | |

## 3.4 Fatigue Load Calculation

The ability of time domain simulations to capture associated nonlinearities and transient events makes it a common approach for calculating dynamic loads and responses. Sources of nonlinearities include (but are not limited to) blade-pitch and generator-torque behaviour, aeroelastic effects, occurrence of grid errors and short circuits, and nonlinear soil-structure interaction (Vorpahl et al., 2013). Unlike offshore structures for oil & gas applications, OWT loads are highly dependent on wind speed and wind turbine control, and on whether the OWT is in operating or parked condition. Fig. 3.4 illustrates the nonlinear relation between (a) thrust and $U_{hub}$ and (b) power output and $U_{hub}$ for both operating and parked cases.

Although parked OWTs have reduced aerodynamic loads due to the pitching of the blades when wind speed is outside the operational range ($U_{in} < U_{hub} < U_{out}$), fatigue contributions during parked conditions can be higher due to reduced aerodynamic damping. A 90-95% wind turbine availability is normally assumed during the design process (Carroll, May, McDonald, & McMillan, 2015). This leads to 5-10% of the fatigue design loads coming from the parked or idling load cases.

Based on the metocean input parameters, the stochastic wind field and wave kinematics are generated. This results in stochastic OWT responses, as illustrated in Fig. 3.5. A good practice in wind turbine load analysis is the investigation of power spectral density (PSD) signals. Comparison of both input (wind and wave) and output (structural response) PSDs can indicate whether responses are sensitive to wind, wave or other excitation frequencies.




(a) Thrust curve (b) Power curve

**Fig. 3.4:** Derived (a) thrust and (b) power curve based on time-domain simulations of DLC 1.2 for the DTU 10 MW reference OWT with six realizations per wind speed. Adapted from Velarde et al. (2019).

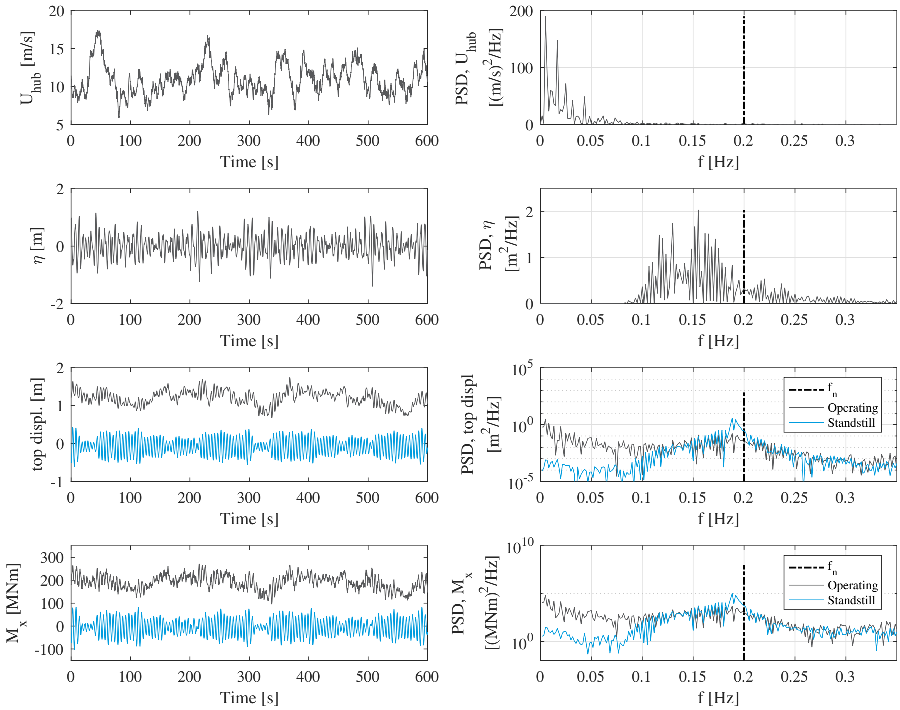



**Fig. 3.5:** Time domain simulation and frequency domain signals of OWT response and selected environmental condition ($U_{hub} = 11\ m/s,\ TI = 0.18,\ H_s = 1.55\ m,\ T_p = 7.4\ s, \gamma_{wave} = 1.0$). The natural frequency ($f_n$) of the 10 MW OWT is also illustrated.

## 3.5 Fatigue Resistance Modeling

The fatigue analysis of both steel and concrete offshore structures is normally performed based on cumulative linear damage theory (Miner et al., 1945; Palmgren, 1924). The total fatigue damage $(D_f)$ can expressed as the sum of all the induced load cycles $(n_i)$ divided by the number of cycles to failure $(N_i)$ as shown in Eq. 3.1.

$$D_f = \sum_{i=1}^{N_S} \frac{n_i}{N_i} \tag{3.1}$$

The fatigue resistance of a material is normally expressed in terms of S-N curves, which are also referred to as the Wöhler curves. The relationship between a stress range (S) and the corresponding number of cycles to failure (N) can be described by the Basquin (1910) equation as shown in Eq. 3.2.

$$N = K \cdot S^{-m} \tag{3.2}$$

where $K$ and $m$ are empirical constants that define the negative inverse slope and intercept, respectively. Both $K$ and $m$ can be determined by performing experimental fatigue tests at different stress ranges. Fig. 3.6 illustrates a stress range cycle for a constant amplitude stress history.

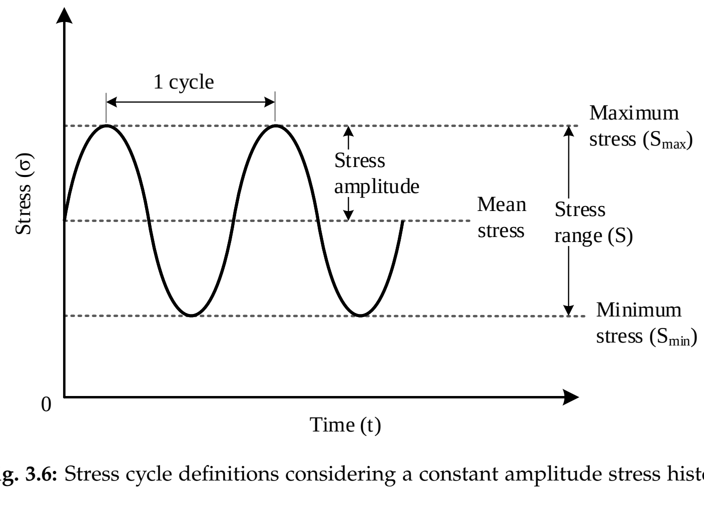



**Fig. 3.6:** Stress cycle definitions considering a constant amplitude stress history

For concrete structures, the mean stress is also an important parameter in defining the fatigue resistance. Therefore, S-N curves for concrete are normally expressed in terms of the minimum $(S_{min})$ and maximum $(S_{max})$ normalised stresses. Based on DNV GL (2016a; 2018a) standards, bilinear

S-N curves for steel and concrete are illustrated in Fig. 3.7a and Fig. 3.7b, respectively. The mean S-N curve for steel is derived based on the distribution parameters found in DNV GL (2016a), while the mean S-N curve for concrete is estimated based on available data for stress ranges defined by $S_{min} = 0.12$ and $S_{max} \geq 0.6$.

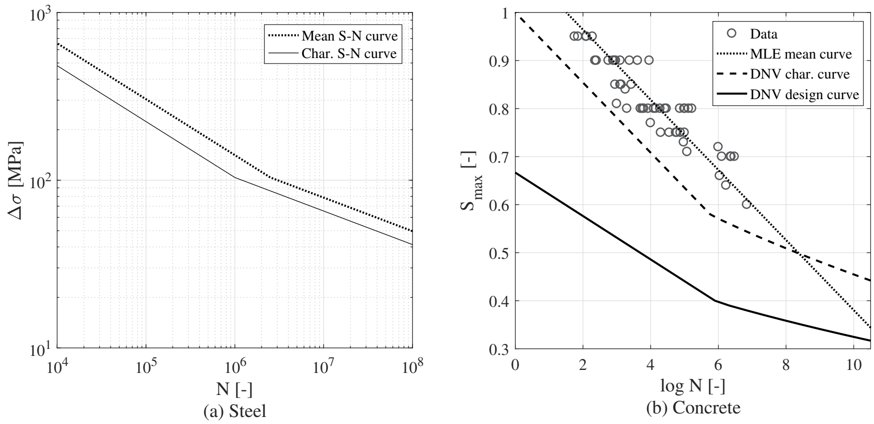



**Fig. 3.7:** S-N curves for (a) steel and (b) concrete based on DNV GL (2016a; 2018a) standards. Adapted from Velarde, Kramhøft, Sørensen, and Zorzi (2019) and Velarde, Mankar, et al. (2019), respectively.

Finally, the total fatigue damage $(D_f)$ is estimated as the cumulative sum of all partial damages from each sea state multiplied by the probability of occurrence $(f)$. A typical $D_f$ distribution across the mean wind speed $(U_{hub})$ and stress range $(S)$ is illustrated in Fig. 3.8. In this case study of an operating 10 MW OWT supported by a monopile, about 40% of the $D_f$ is given by $U_{hub} = 10.5$ - $16.5\ m/s$.

A service life $(T_L)$ of 20 to 25 years is typically assumed for offshore wind turbines. To account for different sources of uncertainties, a fatigue design factor $(FDF)$, also called design fatigue factor $(DFF)$, is considered in the design. For offshore wind turbines, the design equation for fatigue limit state can be generalized as shown in Eq. 3.3.

$$G(\mathbf{z}) = 1 - \sum_{i=1}^{N_{U_w}} \sum_{j=1}^{N_S} \frac{n_{i,j}\ f_i\ FDF\ T_L}{N_j} \tag{3.3}$$

where $N_S$ is the number of stress range bins, $N_{U_w}$ is the total number of lumped sea states and $f_i$ is the corresponding sea state frequency or occurrence probability. Investigations of recommended $FDF$ values for large steel monopiles and concrete GBFs are presented in **Paper E** and **Paper F**, respectively.

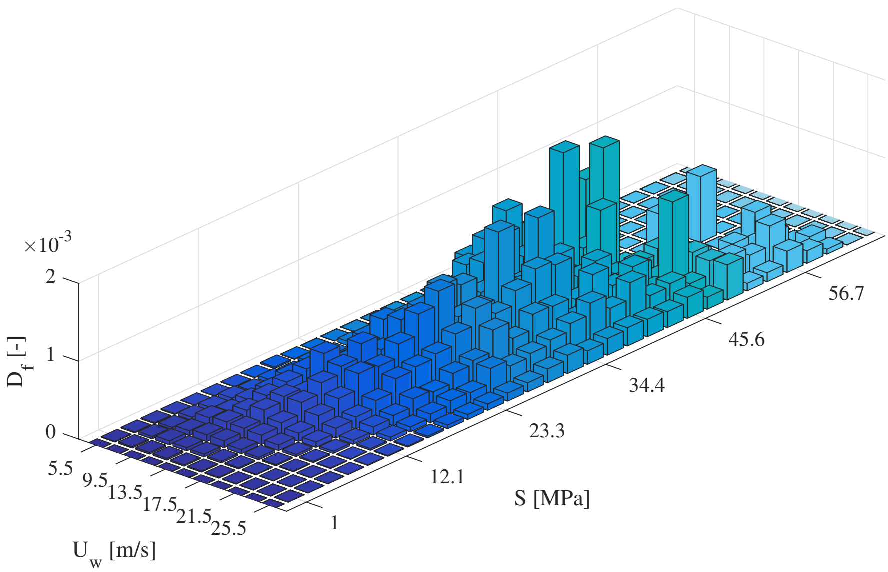



**Fig. 3.8:** Estimated fatigue damage as a function of mean wind speed at hub height ($U_{hub}$) and stress range ($S$) for an operating 10 MW offshore wind turbine supported by a monopile

# Chapter 4

# Reliability Methods in Support Structure Design

## 4.1 Probabilistic Reliability Assessment

The application of classical reliability theory to structural design first gained professional acceptance around the late 1960s. Before then, safety factors that account for the statistical nature of loads, material resistance and workmanship were estimated based on *engineering judgement* (H. O. Madsen, Krenk, & Lind, 2006). These factors, which vary according to the type of structure, were continuously being updated based on accumulated experience.

Today, the use of structural design codes has become a standard practice in engineering. This covers a wide array of applications, including buildings, bridges, railways and aerospace structures, among others. A deterministic or semi-probabilistic approach is normally performed, where partial safety factors are applied to account for the relevant sources of uncertainties. Quantification of uncertainties became possible with the availability of measured data and experimental data.

An alternative to the deterministic approach is the probabilistic design approach, where the important load and resistance parameters are considered as stochastic variables. The probability of failure $(P_F)$ can be estimated for a defined limit state equation and for a given set of stochastic parameters. Although the assessment of uncertain parameters, formulation of limit state equation, and estimation of failure probability can become laborious, probabilistic reliability assessment can result in further design optimization based on the following advantages:

- can account for site-specific data or information
- can account for experimental test results (e.g., fatigue test of a new material, hydrodynamic test of a new design concept)
- can evaluate structural safety for special design conditions not yet covered by structural codes or when limited or no experience exists
- can be used to calibrate and optimize existing deterministic design codes when more data or information is available
- can be used in decision making for lifetime extension and for existing structures when a reassessment is needed (e.g., due to change in load conditions)

DNV GL (2018b) defines reliability as the *ability of a component or a system to perform its required function without failure during a specified time interval*. For a given set of stochastic parameters $\mathbf{X} = \{X_1, X_2, ..., X_n\}$, the limit state equation $(g(\mathbf{X}))$ can be expressed in terms of the load $(S(\mathbf{X}))$ and resistance $(R(\mathbf{X}))$ models as shown in Eq. 4.1. This difference is also referred to as the safety margin $(M(\mathbf{X}))$. By definition, failure occurs if the safety margin or limit state equation is less than or equal to zero (see Eq. 4.2).

$$g(\mathbf{X}) = R(\mathbf{X}) - S(\mathbf{X}) \tag{4.1}$$

$$P_F = P\left(R(\mathbf{X}) - S(\mathbf{X}) \leq 0\right) \tag{4.2}$$

The probability of failure $(P_F)$ is related to the reliability index $(\beta)$ by the standard normal distribution function $\Phi(\cdot)$ as shown in Eq. 4.3. Indicative values based on this relation are summarized in Table 4.1.

$$P_F \approx \Phi\left(-\beta\right) \tag{4.3}$$

**Table 4.1:** Relation between probability of failure $(P_F)$ and reliability index $(\beta)$

| $P_F$ | $10^{-2}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ | $10^{-7}$ |
|---|---|---|---|---|---|---|
| $\beta$ | 2.33 | 3.09 | 3.72 | 4.26 | 4.75 | 5.20 |

Except for a number of special cases, a closed form solution for calculating the $P_F$ does not exist. $P_F$ can be estimated by performing *Monte Carlo* simulations, where a large number of realizations $N_{MC}$ is executed. Given a total number of failures $N_F$, the probability of failure can be approximated as shown in Eq. 4.4. Depending on the complexity of the load and resistance models, the *Monte Carlo* approach can take a considerable amount of computational effort.

$$P_F \approx \frac{N_F}{N_{MC}} \tag{4.4}$$

An alternative to this appoach is the *first-order reliability method* (FORM), where the failure probability is approximated by linearization of the failure surface. Fig. 4.1 graphically illustrates the failure surface in the basic variable (X-space) and the transformed failure surface in the standard normal space (u-space). The estimated first-order $\beta$ corresponds to the minimum distance from the origin to a point in the failure surface at the u-space. The point of linearization is referred to as the design point $(\mathbf{u}^*)$, which, when transformed back to the X-space, gives the design point $\mathbf{X}^*$. A more accurate approximation can be found by the *second-order reliability method* (SORM), which is based on a quadratic approximation to the failure surface (H. O. Madsen et al., 2006).

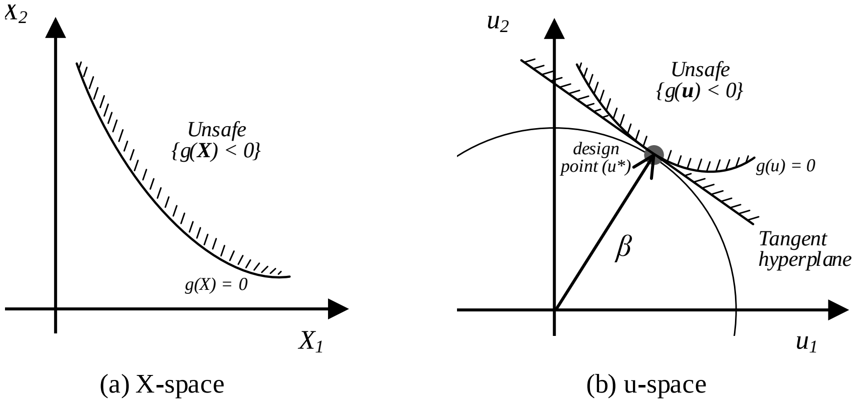



**Fig. 4.1:** Graphical illustration of failure surfaces in (a) X-space and (b) u-space

The sensitivity of $\beta$ to the variation of each stochastic variable $X_i$ at point $\mathbf{X}$, also called the $\alpha_i$ factors, can generally be defined as shown in Eq. 4.5. The relative importance can be assessed based on the definition that $\sum_{i=1} \alpha_i^2 = 1$. At the design point $\mathbf{X}^*$, the corresponding $\alpha_i^*$ factors are also referred to as the *sensitivity factors* (H. O. Madsen et al., 2006).

$$\alpha_i = \frac{\delta \beta}{\delta u_i} \tag{4.5}$$

Several numerical tools are available for reliability calculations. Commercial tools include Proban (DNV), STRUREL (RCP GmbH) and COSSAN (Institute for Risk and Uncertainty, University of Liverpool). Most calculations performed in this research are based on the open access MATLAB-based tool FERUM (Der Kiureghian, Haukaas, & Fujimura, 2006) developed at the University of California, Berkeley, and the probabilistic toolbox PROB2B (TNO).

## 4.2 Related Works

Since early 1980s, structural reliability theories have been applied to the design, operation and maintenance of offshore structures, particularly to oil and gas production platforms. Existing works include investigation of the fatigue design process in welded joints of offshore structures (Wirsching, 1984), application of a stochastic model in fatigue crack growth analysis and demonstration of model updating based on inspection (H. Madsen, Skjong, Tallin, & F, 1987), investigation of the structural reliability and its dependence on design code and environmental conditions (Van de Graaf, Tromans, Efthymiou, et al., 1994), uncertainty modeling in fatigue reliability calculations (Karadeniz, 2001), and assessment of fatigue design criteria considering the effect of inspection (Moan, 2005; Moan, Hovde, Blanker, et al., 1993).

Compared to oil and gas offshore platforms, failure of OWTs generally have lower consequences due to unmanned operations. Thus, a lower target reliability can be accepted for design of OWT structures. Probabilistic design approaches have been mostly applied in design and analysis of wind turbine blades (Ronold, Wedel-Heinen, & Christensen, 1999; Sørensen & Toft, 2010; Toft, Branner, Mishnaevsky Jr, & Sørensen, 2013; Toft & Sørensen, 2011; D. Veldkamp, 2008) and wind turbine components (Nejad, Gao, & Moan, 2014; D. Veldkamp, 2008). For OWT support structures, probabilistic fatigue analyses of steel towers, monopiles and jacket structures were presented in several papers (Dong, Moan, & Gao, 2012; Horn & Leira, 2019; Mai et al., 2019; Márquez-Domínguez & Sørensen, 2012; Sørensen, 2012).

Reliability theories can also be used as a tool for design optimization. Reliability-based design optimization (RBDO) (Enevoldsen & Sørensen, 1994) could deliver cost-effective designs, as demonstrated in the design of tripod (Yang, Zhu, Lu, & Zhang, 2015), monopile transition piece by (Y.-S. Lee, Choi, Lee, Kim, & Han, 2014), monopile and jacket (Muskulus & Schafhirt, 2015) foundations. Moreover, higher levels of reliability methods (i.e., levels II and III) are used for calibration of structural design codes (level I). When more information is available, re-calibration of partial safety factors can lead to significant cost-reductions. Previous investigations of partial safety factors for fatigue strength of steel substructures showed that fatigue design factors can be lowered, while still achieving an acceptable reliability level Márquez-Domínguez and Sørensen (2012); Sørensen (2012). A deeper discussion of reliability methods and its applications to offshore wind energy systems can be found in several review articles (Clark & DuPont, 2018; Jiang, Hu, Dong, Gao, & Ren, 2017; Leimeister & Kolios, 2018).

Finally, it is noted that recommendations regarding probability-based design are also outlined in design standards, including the DNVGL-ST-0126 standard for *Support structures for wind turbines*. Table 4.2 summarizes other relevant standards and guidelines for probabilistic analysis and structural reliability.

**Table 4.2:** Relevant design standards and guidelines for probabilistic design of OWT support structures

| Document code | Title |
|---|---|
| DNVGL-RP-C210 | *Probabilistic methods for planning of inspection for fatigue cracks in offshore structures* |
| IEC 61400-1 (background doc.) | *Safety Factors – IEC 61400-1 ed. 4 - background document* |
| ISO 2394 | *General principles on reliability for structures* |
| JCSS Model Code | *Probabilistic model code* |

## 4.3 Target Reliability Level

The calibration of partial safety factors in design codes requires a target annual reliability index ($\Delta\beta$), which is determined by assessment of the relative cost of safety measures and consequences of failure. Consequences are evaluated in relation to both economic considerations and loss of human lives. Table 4.3 (JCSS, 2001) summarizes tentative target reliability levels related to one year reference period.

**Table 4.3:** Tentative target reliability indices ($\beta$) and associated failure probabilities ($P_F$) related to one year reference period (JCSS, 2001)

| Relative cost of safety measure | Consequences of failure | | |
|---|---|---|---|
| | Minor | Moderate | Large |
| Large | $\beta = 3.1\ (P_F \approx 10^{-3})$ | $\beta = 3.3\ (P_F \approx 5 \cdot 10^{-4})$ | $\beta = 3.7\ (P_F \approx 10^{-4})$ |
| Medium | $\beta = 3.7\ (P_F \approx 10^{-4})$ | $\beta = 4.2\ (P_F \approx 10^{-5})$ | $\beta = 4.4\ (P_F \approx 5 \cdot 10^{-6})$ |
| Small | $\beta = 4.2\ (P_F \approx 10^{-5})$ | $\beta = 4.4\ (P_F \approx 5 \cdot 10^{-6})$ | $\beta = 4.7\ (P_F \approx 10^{-6})$ |

Offshore wind turbines have a relatively large cost of improving safety. Being unmanned structures, these structures are also considered to have minor consequences (class 2) of failure (ISO 2394, 2015). This corresponds to a minimum $\Delta\beta = 3.1$ $\left(P_F \approxeq 10^{-3}\right)$. The target safety level of the normal safety class in the DNVGL (2018b) standard for *Support structures for wind turbines* is a nominal annual $P_F = 10^{-4}$. Since one failure mode is normally governing the design, the target safety level for the entire structure is practically the same as the safety level for the individual failure modes (DNV GL, 2018b). It is noted that this value can vary depending on maintenance strategies and possibility of inspection and repair.

## 4.4 Fatigue Limit State

The global sensitivity analysis performed in **Paper A** showed that the fatigue loads is governed by the TI distribution, particularly at the interface during power production. Thus, probabilistic analyses should account for the TI distribution to avoid overestimation of loads when taking the design value for TI. In the background documentation for IEC 61400-1 (2019a), it is assumed that that the 90% quantile of TI is used in deterministic verification of fatigue. This introduces an 'extra' safety factor that, together with the fatigue partial safety factors, makes sure that the required reliability level is obtained. The probabilistic distribution of TI is considered in fatigue reliability assessments. Fig. 4.2 illustrates the TI distribution as a function of $U_{hub}$ based on the IEC 61400-1 (2005).

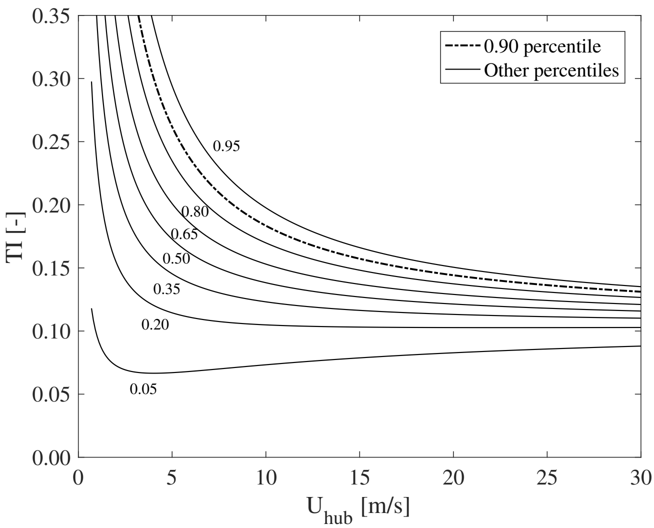



**Fig. 4.2:** Turbulence intensity (TI) distribution and design value (0.90 percentile) based on IEC 61400-1 (2005)

The fatigue limit state equation can be generally expressed as shown in Eq. 4.6, where $n$ gives the number of fatigue load cycles of size $\sigma$ for a given combination of wind speed $(U)$ and turbulence intensity $(TI)$, and $\sigma$ refers to the stress stress ampltiude. The number of cycles to failure $(N)$ is normally expressed by stochastic variables representing the material S-N curve. The stochastic variable $\Delta$, which also depends on the material properties, models the Miner's rule model uncertainty for linear damage accummulation.

$$g(\mathbf{z}, t) = \Delta - \int_{U_{in}}^{U_{out}} \int^{TI} \int_{0}^{\infty} \frac{n(U, TI)\ t}{N(\sigma)}\, d\sigma\, dTI\, dU \tag{4.6}$$

It is noted that other sources of model uncertainty, such as estimation of stress concentration factor $(X_{SCF})$, wind turbine dynamics $(X_{dyn})$ and wave load model uncertainty $(X_{wave})$ can be added if relevant. Moreover, integration over wave parameters $(H_s,\ T_p)$ can also important for wave-sensitive structures. More detailed models that incorporate these uncertainties are included in **Paper E** and **Paper F**.

## 4.5 Ultimate Limit State

Several probabilistic approaches, which are traditionally applied in offshore engineering, can be used to derive the long-term response distribution of OWTs. These include (Haver, 2002; Tarp-Johansen, 2005):

- *All sea states approach*
- *Storm sea state approach*
- *Contour line approach*

The *all sea states approach*, also referred to as the *full long-term analysis* (FLTA) approach, provides the most accurate long-term response because it considers all possible environmental conditions. Eq. 4.7 shows an expression for the extreme long-term cumulative response distribution $(F_{X_{1-hr}})$ of response $X$ considering a 1-hour reference period. The short-term CDF of the 1-hour extreme response, $F'_{X_{1-hr}|u,h,t}\,(x|u,h,t)$, is conditional on the environmental parameters $(U_w, H_s, T_p)$. The joint PDF of the wind and wave parameters, $f_{U_w,H_s,T_p}\,(u,h,t)$, represents the inherent randomness associated with the joint environmental PDF. Although FLTA provides an accurate long-term response distribution, the method has the main disadvantage of being computationally expensive. A similar approach to FLTA is the *storm sea state approach*, which only considers the extreme sea states or storms. This is usually defined by setting a threshold value (e.g., $U_w \geq 30\ m/s$).

$$F_{X_{1-hr}}(x) = \int_u \int_h \int_t F'_{X_{1-hr}|U_w,H_s,T_p}(x|u,h,t)\, f_{U_w,H_s,T_p}(u,h,t)\; du\, dh\, dt \quad (4.7)$$

Another alternative method is the *contour line approach*, also referred to as the *environmental contour method* (Winterstein, Ude, Cornell, Bjerager, & Haver, 1993). In this approach, the uncertainties in the structural response is decoupled with the environmental parameters, since the contours are not related with the structure. The contours are generated based on inverse first-order reliability method (IFORM), where all possible design points are defined for a given failure probability $(P_F)$ or return period $(T_R)$.

Assuming a 1-hour stationary sea state, the 50-year $P_F$ can be approximated as $P_{F50} = 1/(365 * 24 * 50) \approx 2.28 \cdot 10^{-6}$. This corresponds to a reliability index, $\beta_{50} = -\Phi^{-1}(P_F) \approx 4.58$. The contour line can be constructed on a standard Gaussian space as a function of independent standard Normal random variables $(U_1,\ U_2)$. Based on the relation $U_1^2 + U_2^2 = \beta_{50}^2$, the 50-year contour line is illustrated in Fig. 4.3.

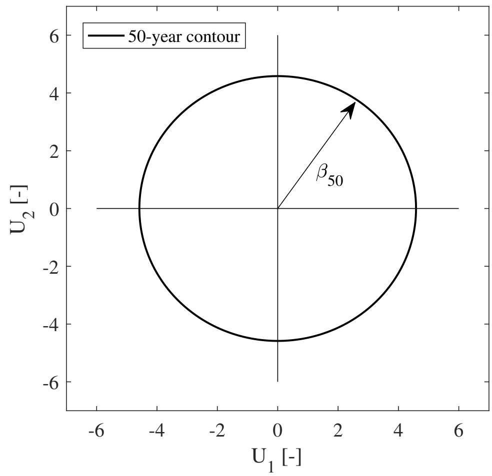



**Fig. 4.3:** Illustration of U-space for $\beta_{50} = 4.58$ (Velarde, Vanem, et al., 2019)

The standard Normal random variables $(U_1,\ U_2)$ can be mapped from the U-space to the physical space by using Rosenblatt transformation (Rosenblatt, 1952). This can be expressed as shown in Eq. 4.8 and Eq. 4.9 for a two-dimensional contour, where $F_{U_w}$ is the mean wind speed $(v)$ marginal distribution funtion and $F_{H_s|U_w}$ is the wave height $(h)$ distribution function conditional to $v$. It is noted that when fitting both $F_{U_w}$ to $F_{H_s|U_w}$ to site data, an appropriate statistical distribution (e.g., extreme value distributions) should be selected such that it satisfactorily models the tail of the distribution. A set of environmental contours for selected annual probability of exceedance $(q)$ is illustrated in Fig. 4.4. The design sea state, which is the $U_w - H_s$ combination that gives the maximum structural response, is defined in each contour line. This normally corresponds to the combination with either the maximum $U_w$, maximum $H_s$ or somewhere in between.

$$\Phi(U_1) = F_{U_w}(v) \tag{4.8}$$

$$\Phi(U_2) = F_{H_s|U_w}(h|v) \tag{4.9}$$

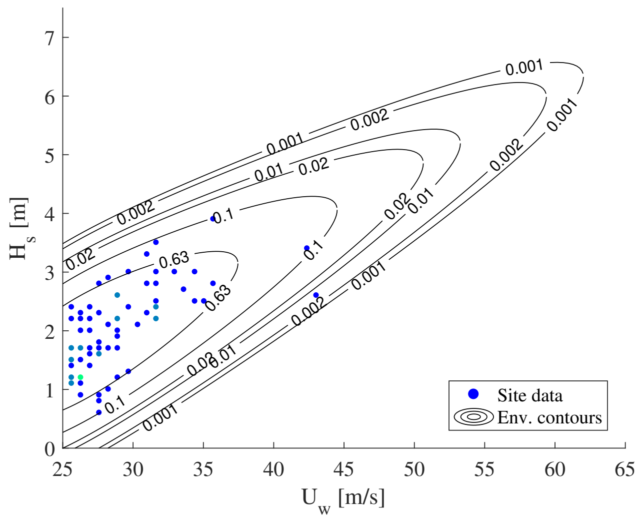



**Fig. 4.4:** Environmental contours based on site data for selected annual probability of exceedance $(q)$. Adapted from Velarde, Kramhøft, and Sørensen (2019b).

Finally, the maximum response distribution can be derived based on the load estimates for each design sea states. For wave-dominated offshore structures, the short-term variability in the structural response can be accounted by inflating the contours (Winterstein et al., 1993). Alternatively, a higher fractile value (e.g., 0.85-0-90 fractile) can be assumed to derive the representative value (Haver, 2002; Winterstein et al., 1993) for the extreme response distribution. The latter approach is illustrated in Fig. 4.5, which also shows that neglecting the short-term variability of the response can lead to underestimation of the loads.

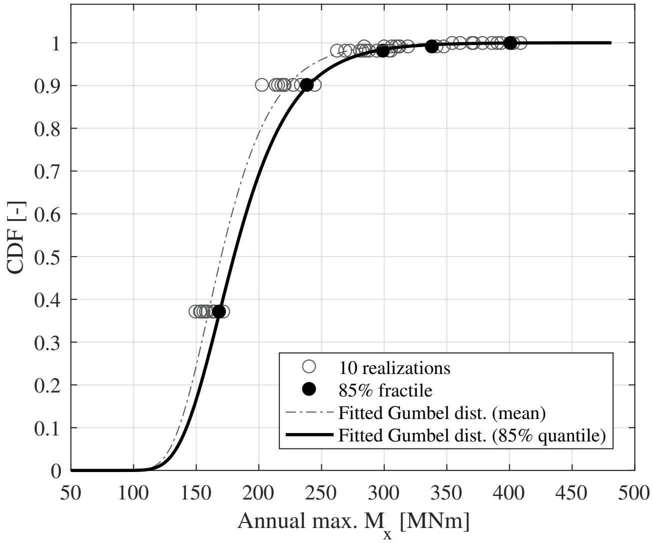



**Fig. 4.5:** Illustration of extreme response distribution at GBF ring beam section. Gumbel distribution is fitted to 0.85 fractile with mean value, $E[M_x] = 187.7\ MNm$ and standard deviation, $\sigma_{M_x} = 40.4\ MNm$. Adapted from Velarde, Kramhøft, and Sørensen (2019b).

Applications of *environmental contour method* in the design and analysis of offshore wind turbines are demonstrated in several papers (Agarwal & Manuel, 2009; C. F. Christensen & Arnbjerg-Nielsen, 2000; Horn & Winterstein, 2018; Li, Gao, & Moan, 2016; Saranyasoontorn, Manuel, et al., 2005).

**Paper C** and **Paper D** of this thesis also applied the *environmental contour method* for derivation of OWT extreme response distribution and reliability analyses.

## 4.6 Design Code Calibration

One of the most adopted design principle is the *load and resistance factor design* (LRFD), where load and resistance partial safety factors are used to deal with the variability in the load (S) and resistance (R) variables. For simplicity, a fundamental case of normally distributed load and resistance variables is illustrated in Fig. 4.7. Normalized probability density functions are plotted for both load and resistance variables. Based on LRFD principle, the design load $(S_d)$ can be obtained by multiplying the characteristic load $(S_c)$ by a load partial safety factor $(\gamma_S > 1.0)$. Similarly, the design resistance $(R_d)$ is obtained by reducing the characteristic resistance $(R_c)$ by the material partial safety factor $(\gamma_m > 1.0)$. Satisfying the design requirement $(S_d \leq R_d)$ results in a rational safety margin, which should ideally correspond to an acceptable failure probability.

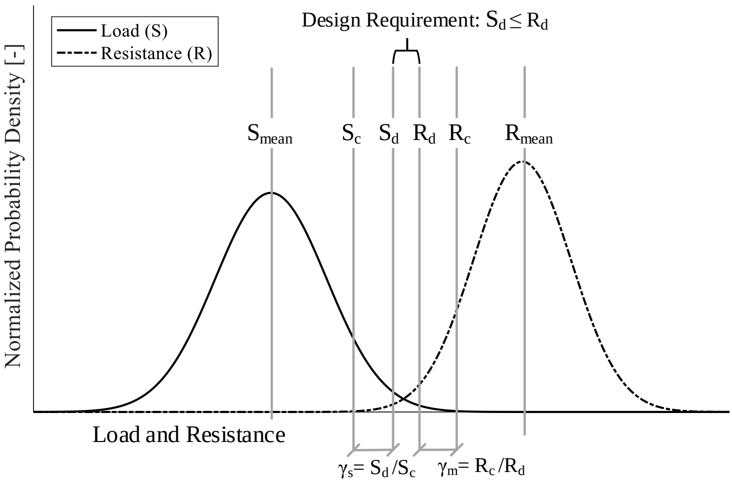



**Fig. 4.6:** Design principle based on load and resistance factor design (LRFD)

Although the illustration above directly relates to extreme load analysis, the same principle is applied for fatigue design of offshore wind turbines. Instead of applying a load factor, characteristic values for turbulence intensity (TI) is recommended in the IEC 61400-1 (2005) standard.

For the fatigue resistance, safety margin is applied by assuming a characteristic S-N curve (see Sec. 3.5). In addition to the load and resistance characteristic values, it is noted that a fatigue design factor (FDF) is also applied in fatigue design (see Eq. 3.3). FDF values account for other factors, such as extreme corrosion if the section is within the splash zone or for sections where fatigue inspection is not possible.

Calibration refers to the process of assigning values to design code parameters (H. O. Madsen et al., 2006). This requires both a design equation and a limit state equation to represent the deterministic and probabilistic analyses, respectively. Fig. 4.7 illustrates a reliability-based approach for calibration of OWT fatigue safety factors $(\gamma_m, FDF)$. The deterministic design approach requires fixed values for input parameters, usually corresponding to the design values $(X_d)$. On the other hand, the probabilistic design approach requires stochastic input variables $(X)$ to represent the same input parameter. The selected design parameter, $z$ (e.g., sectional thickness), relates the safety factors ($\gamma_m$, $FDF$) and the resulting reliability indices ($\beta(z)$). Based on this relation, a set of safety factors can be recommended, such that the target reliability level ($\beta_t$) is fulfilled.

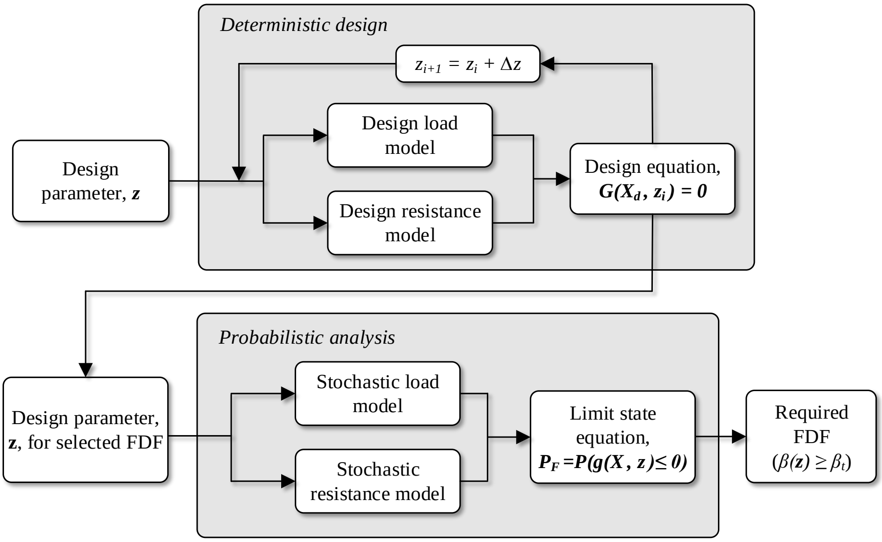



**Fig. 4.7:** Reliability-based approach for calibration of materal partial safety factor, ($\gamma_m$) and fatigue design factors (FDFs). Adapted from Velarde, Mankar, et al. (2019).

Based on the reliability-based approach illustrated, this Ph.D. thesis investigates the fatigue safety factors for OWT support structures. **Paper E** considers a large steel monopile foundation, while **Paper F** considers a concrete GBF. The effects or consequences of human error are not considered in the reliability analyses.

# Chapter 5

# Conclusions & Further Work

## 5.1 Conclusions

This thesis has the objective to demonstrate applications of probabilistic methods to optimize the design of offshore wind turbine support structures. The main research findings and conclusions that can be drawn from the study are summarized in this section.

**Sensitivity and Uncertainty Analysis**

Integrated wind turbine load analysis requires a number of input parameters to represent the wind turbine structure, soil conditions and metocean environment. Considering the uncertainties on these input parameters, two global sensitivity analysis methods, namely the *Elementary Effects* method and the *Standardized Regression Coefficients (SRC)* method, were demonstrated. The sensitivity of both fatigue and ultimate loads to variation in the input parameters were quantified. The following conclusions, which are found to be consistent in both methods, can be drawn:

- Uncertainties in the environmental parameters (soil, wind and wave) are generally more significant than the uncertainties in the structural parameters (e.g., modulus of elasticity, nacelle mass, hub mass).
- Parameter sensitivity rankings vary according to the design load case considered. As an example, it was shown that the variation in turbulence intensity governs the interface fatigue loads during wind

turbine operation. But during parked or idling situations, uncertainties related to soil stiffness and hydrodynamic loads govern the fatigue loads.

- Fatigue loads at the mudline are highly influenced by the wave load uncertainty. This applies to both operational and parked cases. The same conclusion can be made for the extreme loads at the mudline.

- Uncertainties in geotechnical properties have nonlinear, interactive effects to wind turbine loads. This means that the variation in soil conditions does not significantly affect the load estimates, unless a certain threshold (i.e., very soft soil condition) has been exceeded.

When performing fatigue assessment of wind turbine concrete structures, the uncertainty related to the concrete fatigue damage model $(X_m)$ governs the fatigue life estimate. The importance of performing experimental fatigue tests at lower stress cycle amplitudes to improve estimate of the fatigue model uncertainty is highlighted.

Although the results presented were particularly based on the specific case studies and were limited by the assumptions made, some outcomes are generally valid in most cases. Furthermore, applications of global sensitivity analysis techniques were shown to have several advantages in numerical modeling of OWT loads. By knowing the most relevant sources of uncertainties, model simplification can be done without significantly losing accuracy, and more efforts can be focused on the assessment of the few important parameters. Lastly, knowledge of the model sensitivity has assisted and motivated the succeeding papers with regards to research direction.

**Applications of Extreme Response Analysis**

Offshore wind turbine support structures must be designed such that no failure occurs during combined extreme wind and wave actions. Within the industry and academia, there is currently no common concensus on extrapolation of joint metocean conditions. The *Environmental Contour method* was used to rationally derive the representative design metocean conditions. Based on integrated wind turbine simulations, extreme load response distributions were derived and used as main input in reliability analyses.

Reliability-based design optimization (RBDO) of a concrete GBF was demonstrated. Considering multiple limit state criteria, it was shown that an optimal amount of prestressing steel and steel reinforcement can be found, while satisfying the required reliability level. RBDO can significantly contribute to the cost reductions in OWT support structure.

Within the last three decades, offshore wind turbines have become larger and installations have reached deeper waters. In relation to this trend, a design uncertainty was identified and investigated. During parked conditions, wave-sensitive OWTs can exhibit resonant responses due to moderate sea states with wave period coinciding with the structural eigenfrequency. A case study on a large monopile showed that dyamically amplified loads can potentially govern the design. The analysis was based on a probabilistic framework, which was introduced to address the design uncertainty currently not covered in design codes.

The applications presented highlighted the importance of accounting for site-specific metocean conditions, particularly in design optimization and assessment of design uncertainties. The methodologies presented can also be applied to other types of support structures.

### Fatigue Reliability and Partial Safety Factors

Fatigue design rules for OWT support structures were mostly adopted from the offshore oil and gas industry. In addition to having relatively lower consequences of failure, fatigue safety factors can be investigated when there are changes in the load conditions (e.g., increased wave load contribution to fatigue) or when more data or information is available (e.g., experimental fatigue test data).

This thesis investigated the fatigue reliability of both steel monopile and concrete gravity-based foundation. Probabilistic calibration of fatigue partial safety factors was performed considering the relevant sources of uncertainties identified from the sensitivity analysis. For large monopiles, it was concluded that the currently recommended fatigue design factor, $FDF = 3$, still satisfies safety requirements. But as wave load contribution increases due to larger wind turbine or higher water depth, a higher FDF value should be recommended. For concrete foundations, it was concluded that partial safety factors can be lowered without compromising structural safety.

Investigation of fatigue reliability of support structures can identify the technical and economic limitations of upscaling of monopiles. On the other hand, reduction of fatigue partial safety factors for OWT concrete structures can contribute to design optimization and further cost reductions.

## 5.2 Further Work

A number of related topics within probabilistic design of offshore wind turbine foundations can be further investigated. Recommendations for future work are summarized below.

- Offshore wind turbine loads were estimated using an integrated load model, where the hydrodynamic loads are calculated based on linear wave theory and Morson's equation. Implementation of **better wave load models** in both fatigue and extreme load cases, particularly models that account for nonlinear or higher order effects, can improve reliability estimates.
- Support structures for offshore wind turbines are exposed to a large number of small stress cycles. Performing **high-cycle fatigue tests** to improve S-N curves, particularly for concrete structures, can reduce excessive safety margin in fatigue design rules.
- Fatigue design can be improved by **accounting for inspections and repairs**. This requires both an inspection planning that can account for probability of crack detection and a calibration of fracture mechanics model.
- Installation of a structural health monitoring system in offshore wind turbines can provide information about the actual loads experienced by the structure. **Reliability updating based on monitoring data** can support decisions on risk-based maintenance and lifetime extension of offshore wind turbines.
- The present thesis focuses on FLS and ULS of offshore wind turbine support structures. Considering **other failure modes** (e.g., wind turbine mechanical failure, soil bearing capacity failure) and **system effects** can improve structural reliability estimates.

# References

Agarwal, P., & Manuel, L. (2009). Simulation of offshore wind turbine response for long-term extreme load prediction. *Engineering structures*, *31*(10), 2236–2246.

Andersen, L., Ibsen, L. B., & Liingaard, M. (2009). Lumped-parameter model of a bucket foundation. *Computational Geomechanics: COMGEO I, IC2E International Center for Computational Engineering*, 731–742.

Andersen, L., & Liingaard, M. (2007). Lumped-parameter models for wind-turbine footings on layered ground. *Aalborg University, Department of Civil Engineering DCE Technical Memorandum*.

API. (1989). *Recommended practice for planning, designing, and constructing fixed offshore platforms* (Vol. 2). American Petroleum Institute.

Bachynski, E. E., & Ormberg, H. (2015). Hydrodynamic modeling of large-diameter bottom-fixed offshore wind turbines. In *Asme 2015 34th international conference on ocean, offshore and arctic engineering* (pp. V009T09A051–V009T09A051).

Basquin, O. (1910). The exponential law of endurance tests. In *Proc am soc test mater* (Vol. 10, pp. 625–630).

Benitz, M., Lackner, M., & Schmidt, D. (2015). Hydrodynamics of offshore structures with specific focus on wind energy applications. *Renewable and Sustainable Energy Reviews*, *44*, 692–716.

Beyer, F., et al. (2013). Analysis of floating offshore wind turbine hydrodynamics using coupled cfd and multibody methods. In *The twenty-third international offshore and polar engineering conference.*

Bhattacharya, S., & Adhikari, S. (2011). Experimental validation of soil–structure interaction of offshore wind turbines. *Soil Dynamics and Earthquake Engineering*, *31*(5), 805–816.

Borg, M., Hansen, A. M., & Bredmose, H. (2016). Floating substructure flexibility of large-volume 10mw offshore wind turbine platforms in dynamic calculations. In *Journal of physics: Conference series* (Vol. 753, p. 082024).

Bredmose, H., & Jacobsen, N. G. (2010). Breaking wave impacts on offshore wind turbine foundations: focused wave groups and cfd. In *Asme 2010*

*29th international conference on ocean, offshore and arctic engineering* (pp. 397–404).

Bredmose, H., Skourup, J., Hansen, E., Christensen, E. D., Pedersen, L., & Mitzlaff, A. (2006). Numerical reproduction of extreme wave loads on a gravity wind turbine foundation. In *25th international conference on offshore mechanics and arctic engineering* (pp. 279–287).

Bush, E., & Manuel, L. (2010). The influence of foundation modeling assumptions on long-term load prediction for offshore wind turbines. In *Asme 2009 28th international conference on ocean, offshore and arctic engineering* (pp. 1075–1083).

Camp, T., Morris, M., Van Rooij, R., Van Der Tempel, J., Zaaijer, M., Henderson, A., ... others (2003). Design methods for offshore wind turbines at exposed sites. *Final Report of the OWTES Project, Garrad Hassan and Partners Ltd., Bristol, UK*.

Carroll, J., May, A., McDonald, A., & McMillan, D. (2015). Availability improvements from condition monitoring systems and performance based maintenance contracts. *European Wind Energy Association (EWEA) Offshore 2015*.

Carswell, W., Arwade, S. R., DeGroot, D. J., & Lackner, M. A. (2015). Soil–structure reliability of offshore wind turbine monopile foundations. *Wind Energy*, *18*(3), 483–498.

Chatzigogos, C., Pecker, A., & Salencon, J. (2009). Macroelement modeling of shallow foundations. *Soil Dynamics and Earthquake Engineering*, *29*(5), 765–781.

Christensen, C. F., & Arnbjerg-Nielsen, T. (2000). Return period for environmental loads–combination of wind and wave loads for offshore wind turbines. *EFP'99*.

Christensen, E. D., Bredmose, H., & Hansen, E. A. (2005). Extreme wave forces and wave run-up on offshore wind turbine foundations. *Proceedings of Copenhagen Offshore Wind*, 1–10.

Christensen, E. D., Lohmann, I. P., Hansen, H. F., Haerens, P., Mercelis, P., & Demuynck, A. (2011). Irregular wave loads on a gravity based foundation in shallow water. In *Asme 2011 30th international conference on ocean, offshore and arctic engineering* (pp. 437–446).

Clark, C. E., & DuPont, B. (2018). Reliability-based design optimization in offshore renewable energy systems. *Renewable and Sustainable Energy Reviews*, *97*, 390–400.

Cordle, A., Jonkman, J., et al. (2011). State of the art in floating wind turbine design tools. In *The twenty-first international offshore and polar engineering conference.*

Damgaard, M., Andersen, L. V., Ibsen, L. B., Toft, H. S., & Sørensen, J. D. (2015). A probabilistic analysis of the dynamic response of monopile foundations: Soil variability and its consequences. *Probabilistic*

*Engineering Mechanics*, *41*, 46–59.

Dean, R. G., & Dalrymple, R. A. (1991). *Water wave mechanics for engineers and scientists* (Vol. 2). World Scientific Publishing Co Inc.

Der Kiureghian, A., Haukaas, T., & Fujimura, K. (2006). Structural reliability software at the university of california, berkeley. *Structural Safety*, *28*(1-2), 44–67.

DNV. (2014). Proban - general purpose probabilistic analysis program. *SESAM User Manual*.

DNV GL. (2014a). *Bladed user manual.* Verion.

DNV GL. (2014b). Environmental conditions and environmental loads. *Recommend Practice DNV-RP-C205*.

DNV GL. (2016a). Fatigue design of offshore steel structures. *Recommended Practice DNVGL-RP-C203*, *20*.

DNV GL. (2016b). Loads and site conditions for wind turbines. *Standard DNVGL-ST-0437*.

DNV GL. (2018a). Offshore concrete structures. *Standard DNVGL-ST-C502*.

DNV GL. (2018b). Support structures for wind turbines. *Standard DNVGL-ST-0126*.

Dong, W. (2012). *Time-domain fatigue response and reliability analysis of offshore wind turbines with emphasis on welded tubular joints and gear components* (Phd thesis).

Dong, W., Moan, T., & Gao, Z. (2012). Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection. *Reliability Engineering & System Safety*, *106*, 11–27.

Enevoldsen, I., & Sørensen, J. D. (1994). Reliability-based optimization in structural engineering. *Structural safety*, *15*(3), 169–196.

Fischer, T., De Vries, W., & Schmidt, B. (2010). Upwind design basis (wp4: Offshore foundations and support structures).

Foglia, A., et al. (2014). *Investigations on macro-element modelling of bucket foundations for offshore wind turbines* (Tech. Rep.). Department of Civil Engineering, Aalborg University.

Grue, J., & Huseby, M. (2002). Higher-harmonic wave forces and ringing of vertical cylinders. *Applied ocean research*, *24*(4), 203–214.

Haldar, S., & Babu, G. S. (2008). Effect of soil spatial variability on the response of laterally loaded pile in undrained clay. *Computers and Geotechnics*, *35*(4), 537–547.

Hansen, A. M. (2014). *Implementation of hawc2 interface to wamit* (Tech. Rep.). Technical report, Technical University of Denmark, Department of Wind Energy.

Haver, S. (2002). On the prediction of extreme wave crest heights. In *Seventh international workshop on wave hindcasting and forecasting, banff, ab, canada, oct.*

Helton, J. C., & Davis, F. J. (2003). Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. *Reliability Engineering & System Safety*, *81*(1), 23–69.

Horn, J.-T. (2018). *Statistical and modelling uncertainties in the design of offshore wind turbines* (Phd thesis).

Horn, J.-T., & Leira, B. J. (2019). Fatigue reliability assessment of offshore wind turbines with stochastic availability. *Reliability Engineering & System Safety*, 106550.

Horn, J.-T., & Winterstein, S. R. (2018). Extreme response estimation of offshore wind turbines with an extended contour-line method. In *Journal of physics: Conference series* (Vol. 1104, p. 012031).

Hübler, C., Gebhardt, C. G., & Rolfes, R. (2017). Hierarchical four-step global sensitivity analysis of offshore wind turbines based on aeroelastic time domain simulations. *Renewable Energy*, *111*, 878–891.

Hübler, C. J. (2019). *Efficient probabilistic analysis of offshore wind turbines based on time-domain simulations* (Phd thesis). Hannover: Institut für Statik und Dynamik, Leibniz Universität Hannover.

Institute for Risk and Uncertainty, University of Liverpool. (n.d.). COSSAN. Retrieved from `https://cossan.co.uk/`

International Electrotechnical Commission. (2005). IEC 61400-1 Wind turbines—part 1: Design requirements.

International Electrotechnical Commission. (2009). IEC 61400-3 Wind Turbines—Part 3: Design Requirements for Offshore Wind Turbines.

International Electrotechnical Commission. (2019a). IEC 61400-1 Wind energy generation systems - Part 1: Design requirements.

International Electrotechnical Commission. (2019b). IEC 61400-3-1 Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines.

International Energy Agency. (2019). *Offshore wind outlook 2019 - world energy outlook special report* (Tech. Rep.). Retrieved from `https://www.iea.org/offshorewind2019/`

International Standards Organization. (2015). ISO 2394: General principles on reliability for structures.

JCSS. (2001). Probabilistic model code. *Joint Committee on Structural Safety*.

Jiang, Z., Hu, W., Dong, W., Gao, Z., & Ren, Z. (2017). Structural reliability analysis of wind turbines: A review. *Energies*, *10*(12), 2099.

Jonkman, J., & Musial, W. (2010). Offshore code comparison collaboration (oc3) for iea task 23 offshore wind technology and deployment. *Contract*, *303*, 275–3000.

Jonkman, J. M., Buhl Jr, M. L., et al. (2005). Fast user's guide. *National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/EL-500-38230*.

Karadeniz, H. (2001). Uncertainty modeling in the fatigue reliability calculation of offshore structures. *Reliability Engineering & System Safety*, *74*(3), 323–335.

Koukoura, C., et al. (2013). Offshore wind turbine foundation model validation with wind farm measurements and uncertainty quantification. In *The twenty-third international offshore and polar engineering conference.*

Krolis, V. D., van der Zwaag, G. L., & de Vries, W. (2010). Determining the embedded pile length for large-diameter monopiles. *Marine Technology Society Journal*, *44*(1), 24–31.

Kühn, M. J. (2001). *Dynamics and design optimisation of offshore wind energy conversion systems*. DUWIND, Delft University Wind Energy Research Institute.

Larsen, T. J., & Hansen, A. M. (2015). How 2 hawc2, the user's manual. *target*, *2*, 2.

Lee, C.-H. (1995). *Wamit theory manual*. Massachusetts Institute of Technology, Department of Ocean Engineering.

Lee, Y.-S., Choi, B.-L., Lee, J. H., Kim, S. Y., & Han, S. (2014). Reliability-based design optimization of monopile transition piece for offshore wind turbine system. *Renewable Energy*, *71*, 729–741.

Leimeister, M., & Kolios, A. (2018). A review of reliability-based methods for risk analysis and their application in the offshore wind industry. *Renewable and Sustainable Energy Reviews*, *91*, 1065–1076.

Lesny, K., & Wiemann, J. (2006). Finite-element-modelling of large diameter monopiles for offshore wind energy converters. In *Geocongress 2006: Geotechnical engineering in the information technology age* (pp. 1–6).

Li, Q., Gao, Z., & Moan, T. (2016). Modified environmental contour method for predicting long-term extreme responses of bottom-fixed offshore wind turbines. *Marine Structures*, *48*, 15–32.

MacCamy, R., & Fuchs, R. A. (1954). *Wave forces on piles: a diffraction theory* (Tech. Rep.). DTIC Document.

Madsen, H., Skjong, R., Tallin, A., & F, K. (1987). Probabilistic fatigue crack growth analysis of offshore structures, with reliability updating through inspection. In *Marine structural reliability engineering symposium.*

Madsen, H. O., Krenk, S., & Lind, N. C. (2006). *Methods of structural safety*. Courier Corporation.

Mai, Q. A., Weijtjens, W., Devriendt, C., Morato, P. G., Rigo, P., & Sørensen, J. D. (2019). Prediction of remaining fatigue life of welded joints in wind turbine support structures considering strain measurement and a joint distribution of oceanographic data. *Marine Structures*, *66*, 307 - 322. Retrieved from `http://www.sciencedirect.com/science/article/pii/S095183391830217X` doi: https://doi.org/10.1016/j.marstruc.2019.05.002

Marino, E., Giusti, A., & Manuel, L. (2017). Offshore wind turbine fatigue loads: The influence of alternative wave modeling for different turbulent and mean winds. *Renewable Energy*, *102*, 157–169.

Márquez-Domínguez, S., & Sørensen, J. D. (2012). Fatigue reliability and calibration of fatigue design factors for offshore wind turbines. *Energies*, *5*(6), 1816–1834.

Martin, R., Lazakis, I., Barbouchi, S., & Johanning, L. (2016). Sensitivity analysis of offshore wind farm operation and maintenance cost and availability. *Renewable Energy*, *85*, 1226–1236.

Miner, M. A., et al. (1945). Cumulative damage in fatigue. *Journal of applied mechanics*, *12*(3), 159–164.

Moan, T. (2005). Reliability-based management of inspection, maintenance and repair of offshore structures. *Structure and Infrastructure Engineering*, *1*(1), 33–62.

Moan, T., Hovde, G., Blanker, A., et al. (1993). Reliability-based fatigue design criteria for offshore structures considering the effect of inspection and repair. In *Offshore technology conference.*

Morison, J., et al. (1950). The force exerted by surface waves on piles. *Journal of Petroleum Technology*, *2*(05), 149–154.

Morris, M. D. (1991). Factorial sampling plans for preliminary computational experiments. *Technometrics*, *33*(2), 161–174.

Müller, K., & Cheng, P. W. (2018). Application of a monte carlo procedure for probabilistic fatigue design of floating offshore wind turbines. *Wind Energy Science*, *3*(1), 149–162.

Murcia, J. P., Réthoré, P.-E., Dimitrov, N., Natarajan, A., Sørensen, J. D., Graf, P., & Kim, T. (2018). Uncertainty propagation through an aeroelastic wind turbine model using polynomial surrogates. *Renewable Energy*, *119*, 910–922.

Muskulus, M., & Schafhirt, S. (2015). Reliability-based design of wind turbine support structures. In *Proceedings of the symposium on reliability of engineering system, hangzhou, china* (Vol. 1517).

Nejad, A. R., Gao, Z., & Moan, T. (2014). On long-term fatigue damage and reliability analysis of gears under wind loads in offshore wind turbine drivetrains. *International Journal of Fatigue*, *61*, 116–128.

Nova, R., & Montrasio, L. (1991). Settlements of shallow foundations on sand. *Géotechnique*, *41*(2), 243–256.

Page, A. M., et al. (2018). A macro-element pile foundation model for integrated analyses of monopile-based offshore wind turbines. *Ocean Engineering*, *167*, 23–35.

Palmgren, A. (1924). Die lebensdauer von kugellagern. *Zeitschrift des Vereins Deutscher Ingenieure*, *68*(14), 339–341.

Passon, P., & Kühn, M. (2005). State-of-the-art and development needs of simulation codes for offshore wind turbines. In *Copenhagen offshore wind*

*2005 conference and expedition proceedings* (pp. 26–28).

Peng, Z., Wellens, P., & Raaijmakers, T. (2012). 3-d numerical modeling of wave run-up on monopiles. In *Asme 2012 31st international conference on ocean, offshore and arctic engineering* (pp. 327–335).

Philippe, M., et al. (2013). An integrated approach for the representation of concrete gravity based foundations for offshore wind turbines. In *Asme 2013 32nd international conference on ocean, offshore and arctic engineering.*

Popko, W., Vorpahl, F., Zuga, A., Kohlmeier, M., Jonkman, J., Robertson, A., ... others (2012). *Offshore code comparison collaboration continuation (oc4), phase i-results of coupled simulations of an offshore wind turbine with jacket support structure* (Tech. Rep.). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Quallen, S., Xing, T., Carrica, P., Li, Y., Xu, J., et al. (2013). Cfd simulation of a floating offshore wind turbine system using a quasi-static crowfoot mooring-line model. In *The twenty-third international offshore and polar engineering conference.*

RCP GmbH. (n.d.). STRUREL. Retrieved from `http://www.strurel.de/`

Robertson, A., Jonkman, J., Vorpahl, F., Popko, W., Qvist, J., Froyd, L., ... others (2014). *Offshore code comparison collaboration, continuation within iea wind task 30: phase ii results regarding a floating semisubmersible wind system* (Tech. Rep.). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Robertson, A. N., Wendt, F., Jonkman, J. M., Popko, W., Borg, M., Bredmose, H., ... others (2016). OC5 Project Phase Ib: Validation of hydrodynamic loading on a fixed, flexible cylinder for offshore wind applications. *Energy Procedia*, *94*, 82–101.

Ronold, K. O., Wedel-Heinen, J., & Christensen, C. J. (1999). Reliability-based fatigue design of wind-turbine rotor blades. *Engineering structures*, *21*(12), 1101–1114.

Rosenblatt, M. (1952). Remarks on a multivariate transformation. *The annals of mathematical statistics*, *23*(3), 470–472.

Salciarini, D., & Tamagnini, C. (2009). A hypoplastic macroelement model for shallow foundations under monotonic and cyclic loads. *Acta Geotechnica*, *4*(3), 163–176.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., ... Tarantola, S. (2008). *Global sensitivity analysis: the primer*. John Wiley & Sons.

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). Sensitivity analysis in practice: a guide to assessing scientific models. *Chichester, England*.

Saranyasoontorn, K., Manuel, L., et al. (2005). On assessing the accuracy of offshore wind turbine reliability-based design loads from the environmental contour method. *International Journal of Offshore and Polar*

*Engineering*, *15*(02).
Schløer, S., et al. (2012). Effects from fully nonlinear irregular wave forcing on the fatigue life of an offshore wind turbine and its monopile foundation. In *Asme 2012 31st international conference on ocean, offshore and arctic engineering* (pp. 393–402).
Schløer, S., Paulsen, B. T., & Bredmose, H. (2014). Application of cfd based wave loads in aeroelastic calculations. In *Asme 2014 33rd international conference on ocean, offshore and arctic engineering* (pp. V09BT09A056–V09BT09A056).
Seidel, M. (2010). Design of support structures for offshore wind turbines–interfaces between project owner, turbine manufacturer, authorities and designer. *Stahlbau*, *79*(9), 631–636.
Skau, K. S., et al. (2018). A macro-element for integrated time domain analyses representing bucket foundations for offshore wind turbines. *Marine Structures*, *59*, 158–178.
Sørensen, J. D. (2012). Reliability-based calibration of fatigue safety factors for offshore wind turbines. *International Journal of Offshore and Polar Engineering*, *22*(03).
Sørensen, J. D., & Toft, H. S. (2010). Probabilistic design of wind turbines. *Energies*, *3*(2), 241–257.
Tarp-Johansen, N. J. (2005). Partial safety factors and characteristic values for combined extreme wind and wave load effects. *Journal of Solar Energy Engineering*, *127*(2), 242–252.
TNO. (2007). PROB2B.
Toft, H. S. (2010). *Probabilistic design of wind turbines* (Phd thesis). Department of Civil Engineering, Aalborg University.
Toft, H. S., Branner, K., Mishnaevsky Jr, L., & Sørensen, J. D. (2013). Uncertainty modelling and code calibration for composite materials. *Journal of Composite Materials*, *47*(14), 1729–1747.
Toft, H. S., & Sørensen, J. D. (2011). Reliability-based design of wind turbine blades. *Structural Safety*, *33*(6), 333–342.
Toft, H. S., Svenningsen, L., Moser, W., Sørensen, J. D., & Thøgersen, M. L. (2016). Wind climate parameters for wind turbine fatigue load assessment. *Journal of Solar Energy Engineering*, *138*(3), 031010.
Toft, H. S., Svenningsen, L., Sørensen, J. D., Moser, W., & Thøgersen, M. L. (2016). Uncertainty in wind climate parameters and their influence on wind turbine fatigue loads. *Renewable Energy*, *90*, 352–361.
Tran, T., Kim, D., & Song, J. (2014). Computational fluid dynamic analysis of a floating offshore wind turbine experiencing platform pitching motion. *Energies*, *7*(8), 5011–5026.
Vahdatirad, M. J., Andersen, L. V., Ibsen, L. B., Clausen, J., & Sørensen, J. D. (2013). Probabilistic three-dimensional model of an offshore monopile foundation: reliability based approach.

Van Buren, E., & Muskulus, M. (2012). Improving pile foundation models for use in bottom-fixed offshore wind turbine applications. *Energy Procedia*, *24*, 363–370.

Van de Graaf, J., Tromans, P., Efthymiou, M., et al. (1994). The reliability of offshore structures and its dependence on design code and environment. In *Offshore technology conference.*

Van Der Tempel, J. (2006). *Design of support structures for offshore wind turbines* (Phd thesis).

Velarde, J., Kramhøft, C., Sørensen, J., & Zorzi, G. (2019). Fatigue reliability of large monopiles for offshore wind turbines. *Manuscript submitted for publication*.

Velarde, J., Kramhøft, C., & Sørensen, J. D. (2019a). Global sensitivity analysis of offshore wind turbine foundation fatigue loads. *Renewable Energy*. Retrieved from `http://www.sciencedirect.com/science/article/pii/S096014811930360X` doi: https://doi.org/10.1016/j.renene.2019.03.055

Velarde, J., Kramhøft, C., & Sørensen, J. D. (2019b). Reliability-based design optimization of offshore wind turbine concrete structures. *Proceedings of the 13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13, Seoul, South Korea, May 26-30, 2019*.

Velarde, J., Mankar, A., Kramhøft, C., & Sørensen, J. D. (2019). Probabilistic calibration of fatigue safety factors for offshore wind turbine concrete structures. *Manuscript submitted for publication*.

Velarde, J., Vanem, E., Kramhøft, C., & Sørensen, J. D. (2019). Probabilistic analysis of offshore wind turbines under extreme resonant response: Application of environmental contour method. *Applied Ocean Research*, *93*, 101947. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0141118719304328` doi: https://doi.org/10.1016/j.apor.2019.101947

Veldkamp, D. (2008). A probabilistic evaluation of wind turbine fatigue design rules. *Wind Energy*, *11*(6), 655–672.

Veldkamp, H. F. (2006). *Chances in wind energy: a probalistic approach to wind turbine fatigue design* (Phd thesis).

Vorpahl, F., Schwarze, H., Fischer, T., Seidel, M., & Jonkman, J. (2013). Offshore wind turbine environment, loads, simulation, and design. *Wiley Interdisciplinary Reviews: Energy and Environment*, *2*(5), 548–570.

Wandji, W. N. (2017). *Probabilistic design of wind turbine structures: Design studies and sensitivities to model parameters* (Phd thesis).

WindEurope. (2019). Offshore wind in europe: Key trends and statistics 2018. Retrieved from `https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2018.pdf`

Winterstein, S. R., Ude, T. C., Cornell, C. A., Bjerager, P., & Haver, S. (1993).

Environmental parameters for extreme response: Inverse form with omission factors. *Proceedings of the ICOSSAR-93, Innsbruck, Austria*, 551–557.

Wirsching, P. H. (1984). Fatigue reliability for offshore structures. *Journal of Structural Engineering*, *110*(10), 2340–2356.

Yang, H., Zhu, Y., Lu, Q., & Zhang, J. (2015). Dynamic reliability based design optimization of the tripod sub-structure of offshore wind turbines. *Renewable Energy*, *78*, 16–25.

Yde, A., Larsen, T. J., Hansen, A. M., Fernandez, M., Bellew, S., & Plant, F. P. (2015). Comparison of simulations and offshore measurement data of a combined floating wind and wave energy demonstration platform. *Journal of Ocean and Wind Energy*.

Zaaijer, M. (2006). Foundation modelling to assess dynamic behaviour of offshore wind turbines. *Applied Ocean Research*, *28*(1), 45–57.

Ziegler, L., & Muskulus, M. (2016). Fatigue reassessment for lifetime extension of offshore wind monopile substructures. In *Journal of physics: Conference series* (Vol. 753, p. 092010).

# Paper A

## Global sensitivity analysis of offshore wind turbine foundation fatigue loads

Joey Velarde, Claus Kramhøft, & John Dalsgaard Sørensen

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# Paper B

## Uncertainty modeling and fatigue reliability assessment of offshore wind turbine concrete structures

Joey Velarde, Claus Kramhøft, Amol Mankar & John Dalsgaard Sørensen

Published in *International Journal of Offshore and Polar Engineering* Vol. 29, No. 2 pp. 165–171, 2019.

# Paper C

## Reliability-based design optimization of offshore wind turbine concrete structures

Joey Velarde, Claus Kramhøft & John Dalsgaard Sørensen

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# Paper D

## Probabilistic analysis of offshore wind turbines under extreme resonant response: Application of environmental contour method

Joey Velarde, Erik Vanem, Claus Kramhøft, & John Dalsgaard Sørensen

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# Paper E

## Fatigue reliability of large monopiles for offshore wind turbines

Joey Velarde, Claus Kramhøft, & John Dalsgaard Sørensen

Submitted to *International Journal of Fatigue*

# Paper F

## Probabilistic calibration of fatigue safety factors for offshore wind turbine concrete structures

Joey Velarde, Amol Mankar, Claus Kramhøft, & John Dalsgaard Sørensen

Submitted to *Engineering Structures*

# Curriculum Vitae

## Joey Velarde

## Education

| | |
|---|---|
| 11/2016 - 10/2019 | **Ph.D. in Civil Engineering**<br>Aalborg University (AAU), Denmark |
| 09/2014 - 06/2016 | **M.Sc. in Offshore Engineering and Wind Turbine Technology**<br>Delft University of Technology (TU Delft), The Netherlands; and Norwegian University of Science & Technology (NTNU), Norway |
| 06/2007 - 04/2012 | **B.Sc. in Civil Engineering**<br>University of the Philippines Los Baños (UPLB), Philippines |

## Fields of Interest

Offshore wind energy, support structure design, integrated load analysis, uncertainty modelling, probabilistic design, reliability & risk analysis

# SUMMARY

There is a growing interest in applications of probabilistic methods in design of offshore wind turbines. As opposed to the classical, deterministic design approach, the probabilistic design approach has the advantage of being able to account for site-specific information, experimental test results and availability of better models. This often leads to more cost-effective design solutions.

This Ph.D. thesis explores the applications of probabilistic methods in design and analysis of offshore wind turbine support structures. Some fundamental aspects and considerations are presented, including global sensitivity analysis of numerical load models, structural reliability analysis under fatigue and extreme loads, and reliability-based calibration of fatigue partial safety factors. This work provides valuable insights to researchers and engineers specializing on the fields of support structure design, reliability analysis and risk assessment.

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