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A COMPARATIVE FATIGUE RELIABILITY STUDY FOR KEY STRUCTURAL COMPONENTS OF OFFSHORE WIND TURBINES

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In this paper, the fatigue reliability of blade root and tower base of a jacket wind turbine, the OC4 semi-submersible wind turbine and a land-based wind turbine is investigated and compared. The fatigue reliability of mooring line and key tubular members of the semi-submersible floater of the OC4 wind turbine is also investigated. The main uncertainties associated with the fatigue reliability analysis are highlighted and estimated. The reliability level of blade root, tower base, mooring line and key tubular members of the OC4 wind turbine corresponding to different design fatigue factors is estimated. The main parameters influencing the fatigue reliability analysis of the key structural components of the OC4 wind turbine are identified. The applicability of reliability analysis method on the structural design of offshore wind turbines is highlighted through the analysis performed in this paper.

Keywords: fatigue, reliability, offshore wind turbine.

1 Introduction

Offshore wind industry is a rapid growing industry in recent decades with large potential to contribute significantly to future electricity production. In 2016, 361 offshore wind turbines (OWTs) of an average capacity rating of 4.8 megawatt (MW) per turbine were constructed in Europe [1]. Almost 70% of the world's cumulative offshore capacity was installed in the North Sea due to its favorable wind resources and shallow water conditions. However, the current levelized cost of energy (LCOE) for offshore wind is still higher than the one for onshore. LCOE is the total cost to build and operate a whole offshore wind turbine structure over its lifetime divided by the total energy output of the wind turbine over that lifetime. How to increase the reliability of offshore wind turbines (OWTs) and to decrease their cost is a focus for wind turbine manufacturers and operators. Cheaper and more efficient wind turbine components have to be developed to have an optimal balance between the initial costs (that is governed by the design corresponding to the required reliability level) and the cost of operation and maintenance. The estimation of the reliability level of key structural components is important for this optimization. It should be noted that the performance of OWTs is subject to a number of uncertainties, which are caused by inherent physical randomness and uncertainties associated with the models used to estimate their performances. A reasonable assessment of these uncertainties is the essence for the estimation of the reliability level of OWTs. In addition, it will be also interesting to see the different response levels, fatigue damages or reliability levels of the structural components (such as blade and tower) or the mechanical components (such as gears, bearings in the drivetrain) as compared to the onshore wind turbines when the same wind turbines are placed on the bottom-fixed or floating foundations.

Presently a semi-probabilistic approach for the structural design of OWTs is suggested by the IEC standards [2][3]. In this approach, a set of design load cases covering various scenarios is considered, and short-term numerical simulations of a validated wind turbine model are performed for the design load cases. To estimate higher load levels for a long-term exceedance probability, extrapolation methods are usually adopted [4][5]. For fatigue limit state design, a design SN curve is usually chosen and a design fatigue factor is determined on the basis of whether inspections will be performed. Then, partial safety factors for loads and materials according to certain reliability levels suggested in the standards are applied in the design check of the fatigue limit states. Through the use of partial safety factors, a consistent reliability level is achieved for the structural components in various load conditions. However these partial safety factors are based on normal design, which are not available for a novel design or an unexpected operating scenario implying a high level of conservatism in a prudent engineering assessment.

Structural reliability analysis (SRA) provides an explicit approach to the uncertain or random nature of loads and capacities and leads to an assessment of the reliability of a structural component or an entire structure. SRA can describe loads and capacities more completely than the deterministic approach using the characteristic values in standard design procedures, which represents the most advanced method for structure design and can be also used in design optimization. Recently a comprehensive review for the structural reliability analysis of wind turbines was performed by Jiang et al. [6], which highlights the importance and benefits of the application of SRA for the design of OWTs. The main steps in a SRA are shown in Figure 1(a). Target reliabilities for a specific design have to be met in order to ensure that certain safety levels are satisfied. A reliability analysis can be used to verify that such a target reliability is achieved for a structure or structural component. The minimum target reliability level for offshore wind turbines can be assessed by different considerations. For manned and unmanned offshore steel jacket structures for oil&gas production maximum annual probabilities of failure of the order 10^{-5} and 10^{-4} are generally accepted, see, e.g. DNV GL RP C203 [7] and DNV GL RP C210 [8]. For offshore wind turbines a target reliability level corresponding to unmanned structures or even lower can be relevant. Presently no explicit target reliability levels are given for the partial safety factors in IEC 61400-3: 2009 [3] for offshore wind turbines. However, the implicit reliability level in the design standards of offshore wind turbines by DNV [9] and GL [10] can alternatively be estimated using an available reliability analysis together with the partial safety factors recommended in these standards. A detailed estimation procedure was suggested by Marquez-Dominguez and Sørensen [11].

Another important application of SRA is for risk-based inspection planning using pre-posterior Bayesian decision theory, which are the basis for assessing the condition of the installation and thus form a cornerstone in the Inspection, Maintenance and Repair (IMR) activities. For offshore wind turbines, operation and maintenance (OM) contribute with a substantial part of the total life cycle costs and can be expected to increase with the increment of water depth of wind farms and in harsher environments. Deterioration mechanisms such as fatigue, corrosion, wear and erosion suffer significant uncertainty. The reliability of prediction can be increased through observations of the degree of damage, especially in connection with condition-based maintenance. Risk-based inspection planning can optimize the time for conditioned maintenance using observations from e.g. condition monitoring and inspections on site. For offshore oil and gas installations, cost-effective procedures for RBI planning have been developed during the last decades and are used at different locations worldwide, see e.g. Moan [12], Faber et al. [13] and Sørensen et al. [14]. A detailed guideline for use of probabilistic methods for inspection planning of fatigue cracks in jacket structures, semisubmersibles and floating production vessels is recommended in DNV GL RP C210 [8]. For offshore wind turbines, Sørensen [15] suggested the procedures for RBI planning based on a similar theoretical basis, which can be used for gearboxes, generators, fatigue cracks, corrosions, etc. In addition, SRA is also applicable to design of new structures, calibration of safety factors in simplified design procedures, reassessment of existing structures taking explicit account of uncertainties in deterioration due to corrosion and wear, decision making under uncertainty and the calculation of probabilities for a wide range of events, etc.

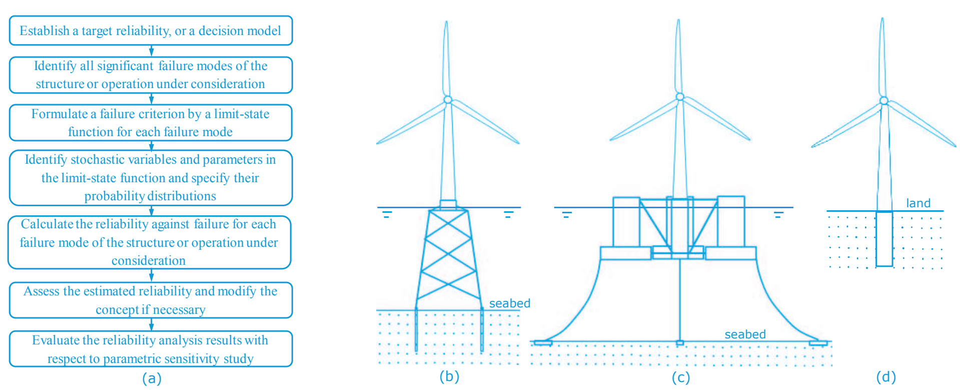


Figure 1. The main steps in a structural reliability analysis (a) and selected wind turbines: (b) Jacket-type offshore wind turbine; (c) Semi-submersible offshore wind turbine; (d) Land-based wind turbine.

In this paper, fatigue reliability analysis of blade root and tower base of a jacket wind turbine, the OC4 semi-submersible wind turbine and a land -based wind turbine as shown in Figure 1 (b)(c)(d) for 5 different offshore sites is performed and compared. The fatigue reliability of mooring line and tubular members of the OC4 semi-submersible wind turbine for the 5 offshore sites is also investigated. Where the same long-term and short-term wind conditions for all three wind turbine concepts and the wave conditions are only considered for the OC4 semi-submersible wind turbine, and long-term fatigue analysis for all three wind turbine concepts is performed considering only normal operational conditions of the wind turbines. The main uncertainties associated with the fatigue reliability analysis are highlighted and estimated. The reliability level of blade root, tower base, mooring line and key tubular members of the OC4 wind turbine corresponding to different design fatigue factors is estimated. The main parameters influencing the fatigue reliability analysis of the key structural components of the OC4 wind turbine are identified. The applicability of reliability analysis method on the structural design of offshore wind turbines is highlighted through the analysis performed in this paper.

2 State-of-the-art reliability analysis of wind turbine components

The literatures on reliability analysis of wind turbines before 1990s are very limited. Veers [16] firstly performed reliability analysis for a vertical axis wind turbine blade. Ronold et al. [17][18] did the structural reliability analysis for the rotor blades of horizontal axis wind turbines at around 2000 years. Afterwards, with the rapid development of computer technology, advanced wind turbine simulation tools came to use in SRA and more probabilistic models of wind turbine structural components were proposed. In general the reliability analysis of wind turbines could be classified into the following categories: rotor blades, bottom-fixed support structures, floating systems, and mechanical and electrical components. First Order Reliability Method (FORM) and Monte Carlo Simulation Method (MCSM) are more often used than other methods. In general FORM is fast but approximate, while MC in principle can be made as accurate as desired at a certain computational effort. In this study only FORM is applied for the fatigue reliability analysis of key structural components of the 3 wind turbines as shown in Figure 1. More details about the status of the application of SRA on wind turbines could be found in [6].

3 Fatigue reliability model

3.1 *Limit state function*

According to Miner's rule, fatigue failure in a structural material can be defined to occur when the cumulative damage D exceeds 1.0, where D is defined as

$$D = \sum_{i=1}^{I} \frac{n_i(S_i)}{N_i(S_i)} \tag{1}$$

where n_i is number of cycles in the stress range i: $\left(s_i - \frac{1}{2}\Delta s,\ s_i + \frac{1}{2}\Delta s\right)$; N_i is number of cycles to failure according to SN curve.

By assuming Weibull distributed stress ranges, the cumulative damage D for a one-slope SN curve can be expressed as follows:

$$D = \frac{N_0}{K} A^m \Gamma\left(\frac{m}{B} + 1\right) \tag{2}$$

where $N_0 = \nu_0 t$ is total number of cycles; K and m are material constants; A is the scale parameter of Weibull distribution; B is the shape parameter of Weibull distribution; ν_0 is number of stress cycles a year; t is time.

By using Eq. (2), the following fatigue limit state function can be defined:

$$M(t) = \Delta - \frac{\nu_0 t}{K} A^m \Gamma\left(\frac{m}{B} + 1\right) \tag{3}$$

where Δ is the Miner's sum at failure.

3.2 *Uncertainty treatment*

For offshore wind turbines, their performances are subject to various uncertainties, which are caused by inherent physical randomness and uncertainties associated with the models used to estimate their performances. A rational treatment of these uncertainties in a quantitative manner is very important for reliability analysis at the design stage as well as in service to aid decision-making. The main uncertainties associate with numerical simulations are statistical uncertainty and model uncertainty.

Statistical uncertainty is mainly due to that different sample data sets usually produce different statistical estimators such as the sample mean, std., etc. A detailed investigation of statistical uncertainties associated with numerical simulations of a bottom-fixed offshore wind turbine is presented in [19]. To minimize, or even neglect, the effect of this uncertainty, at least 50-60 minutes' simulation time are suggested [20][21].

Model uncertainty is mainly due to the use of one (or more) simplified relationship (including formulae, analytical and numerical models, and so on) between the basic variables to represent the 'real' relationship or phenomenon of interest such as load effect and resistance models, etc. It can be typically modelled as follows:

$$\chi = \frac{F_{true}}{F_{est.}} \tag{4}$$

where χ represents the model uncertainty associated with a certain physical variable F (e.g., the aerodynamic loads due to wind, the hydrodynamic loads due to waves and hot-spot stresses of welded tubular joints, etc.). F_{true} represents the real value of this variable, and $F_{est.}$ Represents the estimated value of this variable using simplified methods. A detailed investigation of various model uncertainties for offshore wind turbines is given in [19][20].

By using Eq. (3) and Eq.(4), the following modified fatigue limit state function can be obtained:

$$M(t) = \Delta - \frac{v_0 t}{K} \chi_{load}^m \chi_{dyn}^m \chi_{SCF-com}^m \chi_{SCF-ind}^m A^m \Gamma\left(\frac{m}{B} + 1\right) \tag{5}$$

where χ_{load} represents model uncertainties associated with aerodynamic and hydrodynamic loads. χ_{dyn}represents model uncertainties associated with global dynamic response analysis. $\chi_{SCF-com}$ and $\chi_{SCF-ind}$ represents model uncertainties associated with the calculation of stress concentration factors. $\chi_{SCF-com}$ accounts for the fabrications in accuracies and approximations made in the stress calculation or joint classification. $\chi_{SCF-ind}$ accounts for the individual uncertainty levels of the SCFs for each degree of freedom. More details could be found in [20]. Their probability distribution type, mean value and coefficient of variation (C.O.V.) are given in Table 1 [20]. Eq. (5) is the basic function used for the fatigue reliability analysis in this study.

Table 1. Probability distribution of χ_{load} , χ_{dyn}, $\chi_{SCF-com}$ and $\chi_{SCF-ind}$.

Variable	Type	Mean	C.O.V.	
			Jacket wind turbine and land based wind turbine	OC4 wind turbine
χ_{load}	Log-normal	1.000	0.100 1)	0.200 2)
χ_{dyn}	Log-normal	1.000	0.050	0.100
$\chi_{SCF-com}$	Log-normal	1.000	0.050 3)	0.050 3)
$\chi_{SCF-ind}$	Log-normal	1.000	0.200 4)	0.200 4)

1) Only wind loads are considered.
2) Both wind loads and wave loads are considered.
3) They are not considered for blade root and mooring line.
4) They are not considered for blade root and mooring line.

4 Numerical example

4.1 *Reference wind turbines*

In this study 3 different wind turbines as shown in Figure 1 are considered: jacket wind turbine [22], OC4 semi-submersible wind turbine [23] and land-based wind turbine. The wind turbine is NREL 5 MW; the diameter of rotor is 126 m; the rated wind speed is 12 m/s, the cut-in wind speed is 5 m/s, the cut-out wind speed is 25m/s. Pitch control of blades is applied. The 3 wind turbines have the same hub height. The water depth of the OC4 wind turbine is 200 m. The water depth of the jacket wind turbine is 70 m. The length of the land-based wind turbine tower is 67 m.

For the jacket wind turbine and the land-based wind turbine, only wind loads are considered. The dynamic response of them is calculated with the software HAWC2 [24] which is a tool for simulation of wind turbine response in time domain. For the OC4 wind turbine, both wind loads and wave loads are considered. The dynamic response of it is calculated by SIMO/RIFLEX+Aerodyn (SRA)[25][26][27] developed by MARINTEK and Centre for Ships and Ocean Structures (CeSOS) in Trondheim, Norway. SRA has been verified with different type of wind turbines [28]. The model of the OC4 wind turbine is fully coupled.

In this study the aerodynamic loads on the blades are calculated using Blade Element Momentum theory. The turbulence intensity is assumed to be constant (0.15) for all wind speeds. The hydrodynamic load includes first-order wave loads for large columns with potential theory and viscous drag and hydrodynamic loads on the braces and mooring lines based on Morison formula. The irregular waves are modelled by a three-parameter JONSWAP spectrum with a peakedness parameter of 3.3. Only operational conditions of the three wind turbines are considered. The range of 1-h mean wind speed U_w is 4-26 m/s with an increment of 2 m/s; the range of significant wave height H_s is 1-15 m with an increment of 1 m; the range of spectral peak period T_p is 2-24 s with an increment of 2 s. The joint probability density distributions of U_w , H_s and T_p from [29] are used to calculate the cumulative probability of occurrence. Totally 5 different sea sites from [29] are considered: Site15, Site14, Site5, Site3 and Site1. More details about potential European offshore sites could be found in [29]. The time for each simulation is taken as 3 hours to minimize the statistical uncertainty effects.

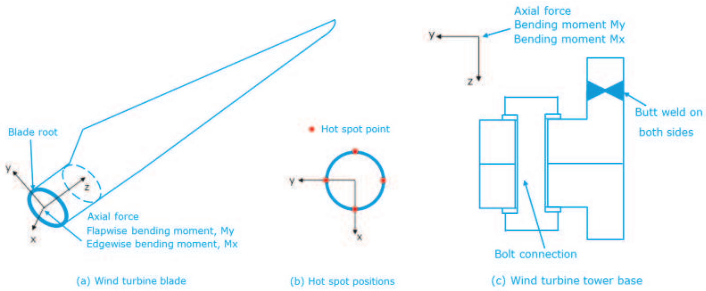


Figure 2. Scheme of hot spot locations considered for wind turbine blade and tower base.

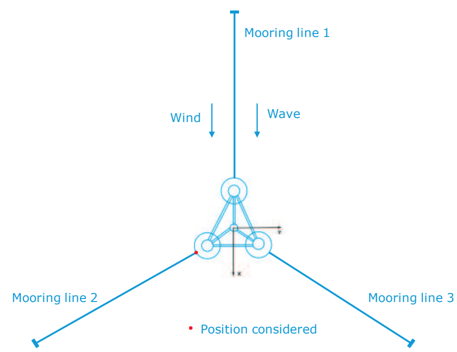
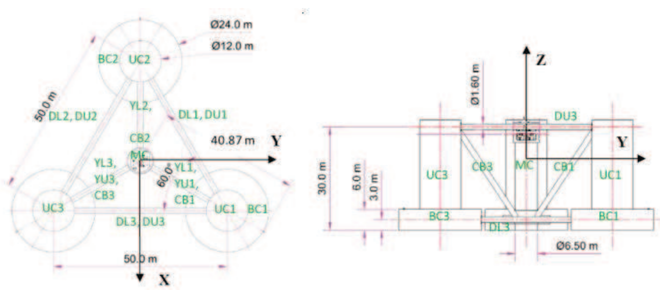


Figure 3. Mooring line arrangement of OC4 wind turbine and position considered.



Member	Type
CB2	Cross Brace 2
DL1	Delta Pontoon, Lower 1
DU1	Delta Pontoon, Upper 1
YU2	Y Pontoon, Upper 1

Figure 4. Tubular members considered for the OC4 semisubmersible wind turbine platform[23].

Table 2. Basic probabilistic material data for fatigue reliability analysis[7][30].

Variable	Distribution	Mean μ	Std. Dev σ	Note
$Log_{10}K$	Normal	12.564	0.200	In air
	Normal	12.164	0.200	With cathodic protection
	Normal	11.550	0.240	Stud link chain
Δ	Log-normal	1.000	0.300	
m	Fixed	3.000		Slope of linear SN curve

4.2 *Hot spot locations and input parameters*

Figure 2 shows the hot spot locations considered for the blade and the tower base of the 3 wind turbines. Figure 3 shows the hot spot locations considered for the mooring line of OC4 wind turbine. Figure 4 shows the hot spot locations considered for the tubular members of OC4 wind turbine platform.

Table 3. Fitting parameters for wind turbine blade and tower in Site14.

Variable	Distribution	Mean μ	C.O.V.[1)]	Note
LnA	Normal	-1.0740	0.010	OC4 WT blade
	Normal	0.2159	0.010	OC4 WT tower
	Normal	0.1062	0.010	Jacket WT blade
	Normal	-0.3043	0.010	Jacket WT tower
	Normal	-0.7408	0.010	Land-based WT blade
	Normal	0.5406	0.010	Land-based WT tower
1/B	Normal	2.2238	0.025	OC4 WT blade
	Normal	1.5461	0.025	OC4 WT tower
	Normal	1.7002	0.025	Jacket WT blade
	Normal	1.5077	0.025	Jacket WT tower
	Normal	2.1697	0.025	Land-based WT blade
	Normal	1.4544	0.025	Land-based WT tower
v_0	Normal	2.58×10^7	0.025	OC4 WT blade
	Normal	5.79×10^7	0.025	OC4 WT tower
	Normal	4.34×10^7	0.025	Jacket WT blade
	Normal	4.32×10^7	0.025	Jacket WT tower
	Normal	1.78×10^7	0.025	Land-based WT blade
	Normal	2.51×10^7	0.025	Land-based WT tower

1) The C.O.V. values are assumed, which are related to the statistical uncertainty. They are identical for all three wind turbine concepts.

Table 4. Fitting parameters for mooring line 2 in Site14.

Variable	Distribution	Mean μ	C.O.V.[1)]	Note
LnA	Normal	0.4709	0.010	Mooring line 2
1/B	Normal	1.8157	0.025	Mooring line 2
v_0	Normal	7.99×10^6	0.025	Mooring line 2

1) The C.O.V. values are assumed, which are related to the statistical uncertainty.

Table 5. Fitting parameters for tubular members of OC4 wind turbine in Site14.

Variable	Distribution	Mean μ	C.O.V.[1)]	Note
LnA	Normal	-0.6624	0.010	CB2
	Normal	-0.3552	0.010	DL1
	Normal	-0.8239	0.010	DU1
	Normal	-0.3948	0.010	YU2
1/B	Normal	2.1377	0.025	CB2
	Normal	2.0913	0.025	DL1
	Normal	2.3310	0.025	DU1
	Normal	2.2506	0.025	YU2
v_0	Normal	4.54×10^7	0.025	CB2
	Normal	2.43×10^7	0.025	DL1
	Normal	2.84×10^7	0.025	DU1
	Normal	3.11×10^7	0.025	YU2

1) The C.O.V. values are assumed, which are related to the statistical uncertainty.

For blade root and mooring line, no SCF is considered in this study. Normal steel material is assumed at blade root. Axial force, flapwise bending moment and edgewise bending moment as shown in Figure 2(a) are considered. Stud link chain is assumed for the mooring lines of OC4 wind turbine, and the probabilistic material data is taken from [30]. Only axial force is considered for the mooring line. For tower base, the butt weld as shown in Figure 2(c) is considered. It is assumed that the tower is made by normal steel instead of high strength steel, and the weld is performed on both sides. A SCF value of 1.54 taken from [7] is assigned to axial force, in-plane bending moment and out-of-plane bending moment respectively. For the tubular members of OC4 wind turbine, it is assumed that normal steel material is applied. A minimum SCF value of 1.5 is assigned to axial force, in-plane bending moment and out-of-plane bending moment at member ends. For blade root, tower base and tubular members of OC4 wind turbine, 4 hot-spot locations as shown in Figure 2(b) are considered and the most critical one with respect to fatigue damage is used in the following fatigue reliability analysis. In addition, the bolt connections at blade root and tower base are not considered in this study. Detailed fatigue analysis procedure for bolt connections could be found in [31][32].

Table 2 shows the basic probabilistic material data for fatigue reliability analysis. Tables 3-5 show the probabilistic data of the Weibull fitting parameters (LnA and 1/B) and the cycle numbers per year ν0 obtained from time domain simulations for blade root, tower base, mooring line 2 and tubular members of OC4 wind turbine respectively. Other types of probabilistic distribution function will be investigated to fit the raw data in future work.

4.3 *The Miner's Fatigue damage*

Table 6 shows the Miner's fatigue damage of different structural components of the 3 wind turbines for 5 different offshore sites using Eq.(2). In the analysis reported in Table 6, the blade root of the jacket WT suffered the largest fatigue damage in all three concepts, and the largest value is 0.160 for Site14. The tower base of the land-based wind turbine suffered the largest fatigue damage in all three concepts, and the largest value is 0.762 for Site14. For mooring line 2, the largest fatigue damage is 0.844 for Site14. For CB2, DL1, DU1 and YU2, the largest fatigue damages are 0.118, 0.407, 0.072 and 0.985 for Site15. Different structural components may have totally different fatigue damage. The effect of different offshore sites on the fatigue damage of a certain structural component seems to be small.

Table 6. The Miner's Fatigue damage for different structural components and offshore sites.

Structures	**Description**	**The Miner's Fatigue damage D (20 years)**				
		Site15	Site14	Site5	Site3	Site1
Blade	Jacket WT	0.138	0.160	0.127	0.129	0.116
	Land-based WT	0.003	0.002	0.002	0.002	0.002
	OC4 WT	0.001	0.001	0.001	0.001	0.001
Tower	Jacket WT	0.009	0.010	0.008	0.008	0.007
	Land-based WT	0.713	0.762	0.566	0.568	0.528
	OC4 WT	0.232	0.213	0.144	0.142	0.120
Mooring line 2	OC4 WT	0.724	0.884	0.689	0.726	0.490
CB2	OC4 WT	0.118	0.117	0.089	0.088	0.080
DL1	OC4 WT	0.407	0.387	0.277	0.274	0.235
DU1	OC4 WT	0.072	0.069	0.054	0.053	0.050
YU2	OC4 WT	0.985	0.973	0.782	0.778	0.750

4.4 *Reliability analysis results and discussion*

The reliability is the complement of the failure probability

$$P_F = P(M(t) \leq 0) \tag{6}$$

and may be expressed in terms of the reliability index $\beta = -\Phi^{-1}(P_F)$, in which Φ denotes the standard Gaussian cumulative distribution function. The reliability is computed by means of a first-order reliability method (FORM) as described by Madsen et al. [33]. The probabilistic analysis program PROBAN, see Tvedt [34], is used for this purpose.

Marquez-Dominguez and Sørensen [11] suggested the minimum acceptable reliability level for fatigue failure of OWTs based on the design fatigue factors suggested in DNV [9] and GL[10]. In this study the minimum reliability level with respect to different design fatigue factor (DFF) value suggested in [11] is used as a reference to judge the reliability level of the structural components of the 3 wind turbines during their service lives.

Wind turbine blade roots Figure 5 (a) shows the reliability index of blade root of the OC4 wind turbine as a function of year for different offshore sites. Figure 5 (b) shows the comparison results of the reliability index of blade roots of the 3 wind turbines as a function of time for Site 14. In the analysis reported in Figure 5 (a) the effect of different environmental conditions on fatigue reliability analysis of blade root is very limited. If it is assumed that blade root is a failure critical detail with access, the DFF value might be taken as 2.0 and the required minimum reliability index might be taken as 2.0[11]. The blade root seems to be robust and satisfy the required fatigue reliability level for all 5 offshore sites. It should be noted that no SCF values are considered in this study, which will be investigated in future work. In the analysis reported in Figure 5 (b) the blade root of the land-based wind turbine has the highest reliability level for offshore Site14, and the blade roots of the jacket wind turbine and

OC4 wind turbine have similar reliability level at the end of 20 years' service life. Higher uncertainty level is assigned to the calculated environmental loads of the OC4 wind turbine which decreases the reliability index of blade root. In addition, different types of support structures also have some effects on the fatigue behavior of blade root, and influence the fatigue reliability analysis results.

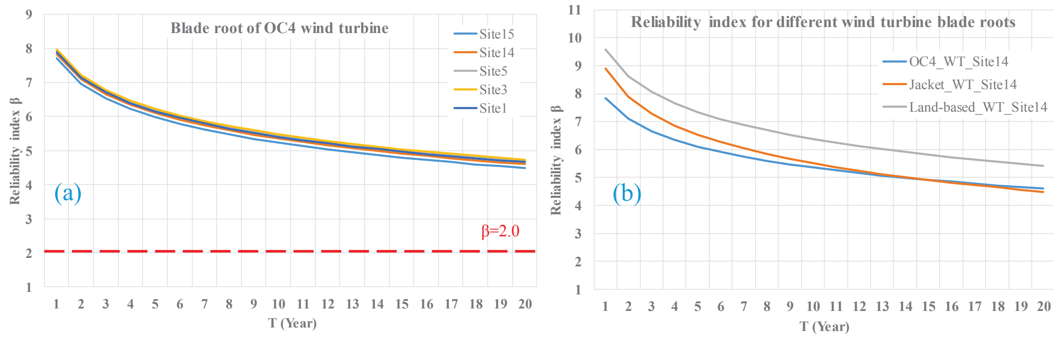


Figure 5. (a) reliability index as a function of time for blade root of OC4 wind turbine. (b) comparison of reliability index as a function of time for blade roots of the three wind turbines.

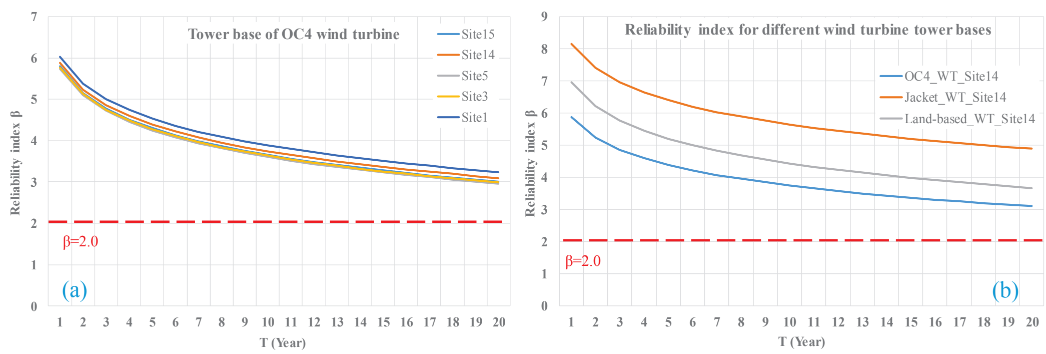


Figure 6. (a) reliability index as a function of time for tower base of OC4 wind turbine. (b) comparison of reliability index as a function of time for tower bases of the three wind turbines.

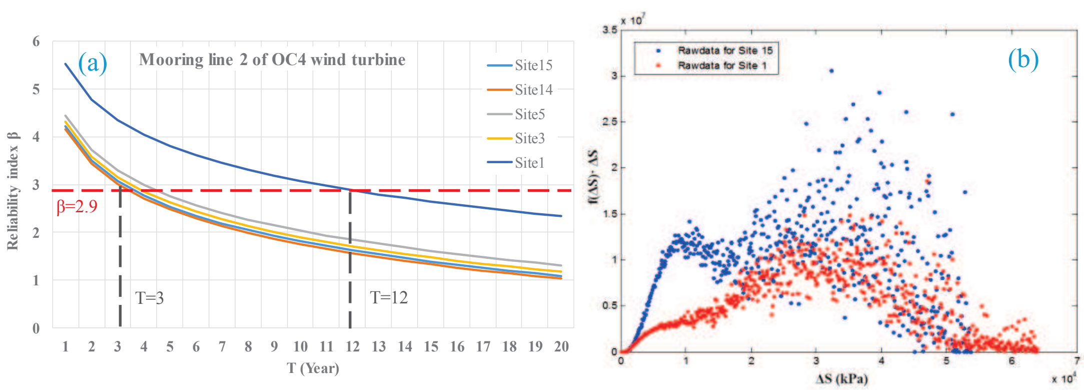


Figure 7. (a) reliability index as a function of time for mooring line 2 of OC4 wind turbine. (b) fatigue damage distribution of mooring line 2 for offshore Site15 and Site1.

Wind turbine tower bases Figure 6 (a) shows the reliability index of tower base of the CO4 wind turbine as a function of year for different offshore sites. Figure 6 (b) shows the comparison results of the reliability index of tower bases of the 3 wind turbines as a function of time for Site 14. In the analysis reported in Figure 6 (a), the effect of different environmental conditions on fatigue reliability analysis of tower base is a little bit larger than that of blade root but still limited. However the reliability level of tower base is much lower than that of the blade root. If the tower base is also assumed as a failure critical detail with access, no inspection is needed for all 5 offshore sites. In the analysis reported in Figure 6 (b) the OC4 wind turbine had the lowest reliability level and the jacket wind turbine has the highest reliability level for offshore Site14. The main reason is that higher uncertainty level is assigned to the calculated environmental loads of the OC4 wind turbine, and the effect of the jacket support structure on the fatigue behavior and the fatigue reliability analysis of tower base is much larger than that of the semi-submersible support structure. It should be noted that wave loads are not considered for the jacket wind turbine, which may have some influence on the fatigue behavior and the fatigue reliability of its tower base and will be investigated in future work.

Mooring line 2 of OC4 wind turbine Figure 7 (a) shows the reliability index of mooring line 2 of the OC4 wind turbine as a function of year for different offshore sites. In the analysis reported in Figure 7 (a) the effect of different environmental conditions on fatigue reliability analysis of mooring line 2 is significant. The reliability level is much lower than that of tower base for all 5 offshore sites. If it is assumed that mooring line is a failure critical detail without access. The DFF value might be taken as 3.0 and the required reliability index could be taken as 2.9[11]. For offshore Site 1, the reliability level will be less than 2.9 in the 12th year after starting service. For the other 4 offshore sites, the fatigue reliability analysis results are much worse as they have much more fatigue damage as shown in Table 6. Figure 7 (b) shows the difference of the fatigue damage point distributions between Site15 and Site1, which will influence the 2-parameter Weibull distribution, especially for fitting the shape parameter B. Table 7 shows the analysis results of importance factors for different structural components. For mooring line 2 χ_{load}, Lg10K, Δ and χ_{dyn} are the same for all 5 offshore sites. The only difference is the value of 1dB. The estimated value of 1dB of Site15 is 1.16 times than that of Site1, which could explain the big difference of the reliability level between Site 15 and Site1. Therefore a reasonable assessment of the shape parameter B is important to have an accurate fatigue reliability analysis of mooring line. In addition, further investigation on uncertainty level of χ_{load}, χ_{dyn} and 1dB should be performed to obtain more reasonable reliability analysis results.

Table 7. Importance factors for different members of OC4 wind turbine semi-submersible platform.

Variables	**Importance factor (%)**				
	Mooring line 2	**CB2**	**DL1**	**DU1**	**YU2**
1dB	8.7	8.2	7.4	9.9	9.2
$\chi_{SCF-ind}$	---	29.0	29.3	28.5	28.7
χ_{load}	38.6	29.0	29.3	28.5	28.7
Lg10K	33.4	17.4	17.6	17.1	17.2
Δ	9.4	7.1	7.1	6.9	7.0
v_0	0.1	0.1	0.1	0.1	0.1
χ_{dyn}	9.8	7.4	7.4	7.2	7.3
$\chi_{SCF-com}$	---	1.8	1.9	1.8	1.8
LnA	0.0	0.0	0.0	0.0	0.0

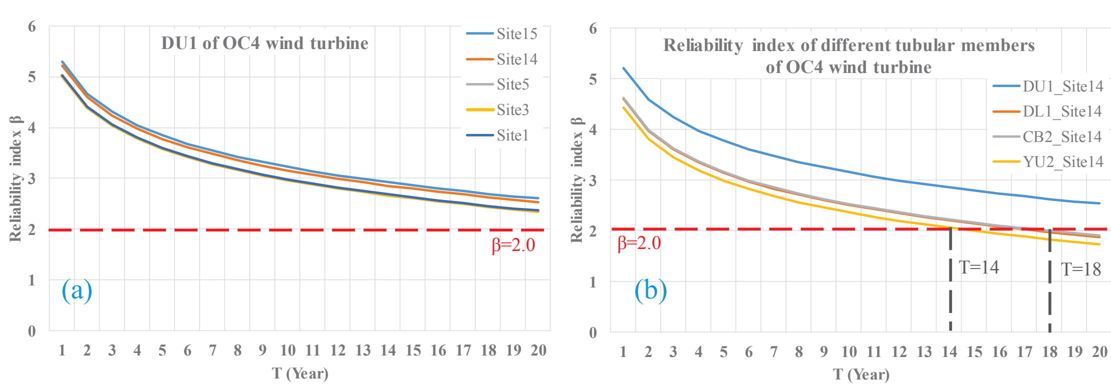


Figure 8. (a) reliability index as a function of time for DU1 of OC4 wind turbine. (b) comparison of reliability index as a function of time for DU1, DL1, CB2 and YU2 of OC4 wind turbine.

Tubular members of OC4 wind turbine Figure 8 (a) shows the reliability index of tubular member DU1 of the OC4 wind turbine as a function of year for different offshore sites. Figure 8 (b) shows the comparison results of the reliability index of DU1, DL1, CB2 and YU2 of the OC4 wind turbine as a function of time for Site 14. In the analysis reported in Figure 8 (a), the effect of different environmental conditions on fatigue reliability analysis of DU1 is larger than that of blade root and tower base but less than that of mooring line 2. If DU1 is assumed to be a failure critical detail with access, no inspection is needed for all 5 offshore sites. In the analysis reported in Figure 8 (b) the difference of the reliability levels of DU1, DL1, CB2 and YU2 for Site14 is significant. DU1 has the highest reliability level and YU2 has the lowest reliability level. For DL1, CB2 and YU2 inspections are needed. The probable first inspection time should be latest on the 14th service year for YU2 and on the 18th service year for DL1 and CB2. It should be noted that a reasonable assessment of the shape parameter B and its uncertainty level is also important to have an accurate fatigue reliability analysis of DU1, DL1, CB2 and YU2, as the contributions from 1dB are big as shown in Table 7.

5 Conclusions

In this paper, the fatigue reliability of blade root and tower base for a jacket wind turbine, the OC4 semi-submersible wind turbine and a land-based wind turbine for 5 different offshore sites is investigated and compared. The fatigue reliability of mooring line and tubular members of the OC4 semi-submersible wind turbine for the 5 offshore sites is also investigated. The conclusions are based on the following assumptions:

(1) The wind and waves always come from the same direction and their phasing is stochastic and non-correlated.
(2) Normal steel material is assigned to blade root and tower base. The effect of bolt connection is not considered.
(3) Linear SN curve model is applied, and the slope of the SN curve m is taken as 3.0.
(4) Simplified SCF values are assigned to tower base and tubular members of OC4 wind turbine. No SCF value is considered for blade root and mooring line.
(5) Stud link chain is assigned to the mooring line of OC4 wind turbine.

The main conclusions obtained in this study based on the above assumptions are as follows:

(1) The fatigue reliability of blade root seems to be not sensitive to different environmental conditions. The effect of different wind turbine support structures on fatigue reliability of blade root is limited.
(2) The effect of different environmental conditions on fatigue reliability of tower base is larger than that of blade root but still limited. The effect of jacket support structure on the fatigue behavior and the fatigue reliability of tower base is much larger than that of semi-submersible support structure.
(3) The effect of the Weibull shape parameter B on fatigue reliability of mooring line and tubular members of the OC4 wind turbine is significant. A reasonable assessment of the Weibull shape parameter B and its uncertainty level is the precondition to have a meaningful fatigue reliability analysis of them. Further investigation will be performed in future work.
(4) Different structural components from the same offshore wind turbine may have different reliability levels and require different inspection plans, even though all of them satisfy the fatigue design criteria
(5) Reliability analysis method can be used to verify the robust of an offshore wind turbine design for its application in different offshore sites. For a key structural component of an offshore wind turbine, its total fatigue damage may be similar for different offshore sites, but its fatigue reliability level as a function of time for different offshore sites may have a big difference.
(6) For mooring line 2 of the OC4 wind turbine, the probable first inspection time according to the fatigue reliability analysis results is too early after starting service, further refined investigation will be performed to clarify the possible reasons in future work.

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