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Energy Procedia 137 (2017) 523–530

Energy Procedia

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14th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2017, 18-20 January 2017, Trondheim, Norway

Lifetime extension for large offshore wind farms: Is it enough to reassess fatigue for selected design positions?

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Abstract

Fatigue reassessment within the decision process of lifetime extension might be uneconomical when individually performed for each turbine of a large offshore wind farm. This paper analyses the possibilities to extrapolate results from fatigue reassessment of wind turbines at selected design positions to other wind turbines of the wind farm. Five monopile-based turbines placed in a generic offshore wind farm were assessed with integrated aero-hydro-elastic simulations. A fatigue assessment was performed for each out of the five selected turbines using site specific environmental data commonly available during the design process. The results were compared to a fatigue reassessment where environmental data were modified in order to account for changes in environmental conditions during the service lifetime of the wind turbines. Results indicate that an extrapolation is feasible for selected parameters when changes in environmental conditions are small. This is an important step towards an effective and efficient assessment methodology for lifetime extension of offshore wind turbines.

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Keywords: Offshore wind turbine; lifetime extension; fatigue reassessment; design position; extrapolation

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10.1016/j.egypro.2017.10.381

1. Introduction

The discussion in the wind industry on lifetime extension of turbines is receiving increasingly more attention. This is naturally driven by the onshore wind industry as more wind turbines are close to the end of their design lifetime already today. Wind turbines are typically designed for 20-25 years and must be decommissioned afterwards. Once lifetime extension becomes important for offshore wind turbines (OWTs) in five to ten years, several issues will differentiate the analysis from onshore. For instance, OWTs are designed site-specifically and turbine downtime may increase loading as pointed out by Ziegler & Muskulus [1]. In addition, offshore wind farms are typically larger, easily inheriting more than 100 turbines. For lifetime extension of onshore wind turbines, every turbine is assessed individually if it has enough structural reserves according to [2]. In large offshore wind farms, however, an individual assessment of every turbine is potentially uneconomic.

Water depth and soil conditions may vary significantly in large offshore wind farms. Ziegler et al [3] presented the influence of site variations on the load level and design process of monopile substructures for OWTs. After several years of turbine operation, measurement data may show that environmental and operational conditions differ from assumptions in the design phase. It is then necessary to reassess fatigue in order to decide if structural reserves are present which potentially allow an extension of the operational life.

Ziegler & Muskulus [1] recently presented fatigue reassessment for monopile-based offshore wind turbines and concluded on the importance to monitor specific parameters during the operational phase of offshore wind parks. Furthermore, it was shown in [4] that wave fatigue loads are sensitive to site conditions. Studies suggested a concept to extrapolate loads from one turbine to the entire wind farm based on in-situ load measurements [5],[6]. However, to the knowledge of the authors, there is no study on the relation between design and numerical fatigue reassessment for different positions within an offshore wind farm.

The purpose of this study is to assess whether it is possible to extrapolate results from fatigue reassessment of selected design positions to the entire wind farm. The study uses a generic wind farm consisting of 100 wind turbines placed in the North Sea. Five turbines of the wind farm with differences in water depth, soil conditions and neighbouring turbines are randomly selected for this study. The numerical models and environmental conditions used for the study are presented in Section 2. Fatigue reassessment is individually performed for each out of the five turbines of the wind farm. Section 3 explains the approach used for the fatigue reassessment and how it is compared with the fatigue assessment in the design process. Results are shown and discussed in Section 4 and a conclusion is drawn in Section 5.

2. Numerical models and environmental conditions

Subject of this study is an offshore wind farm consisting of generic monopile-based offshore wind turbines. The monopile support structure used in Phase II of the OC3 project [7] with the NREL 5MW reference wind turbine atop [8] serves as a reference model. Load simulations were performed for five turbine positions within the generic wind farm. The positions differ in terms of water depth, soil conditions, and wake effects, whereas wave conditions are assumed to be identical for all positions within the wind farm.

2.1. Support structure model

The five OWTs under study with their soil and water depth's conditions at each position in the wind farm are shown in Fig. 1. The height of the rotor and tower bottom with respect to the mean sea level is identical for all turbines. This requires an adjustment of the length of the monopile according to the water depth. A soil penetration depth of 36m is kept constant for all positions.

Table 1. Water depth and first natural frequency of each position.

Parameter	Unit	Pos. 1	Pos. 2	Pos. 3	Pos. 4	Pos. 5
Water depth	[m]	15	20	22	26	30
First natural frequency	[Hz]	0.246	0.237	0.232	0.226	0.217

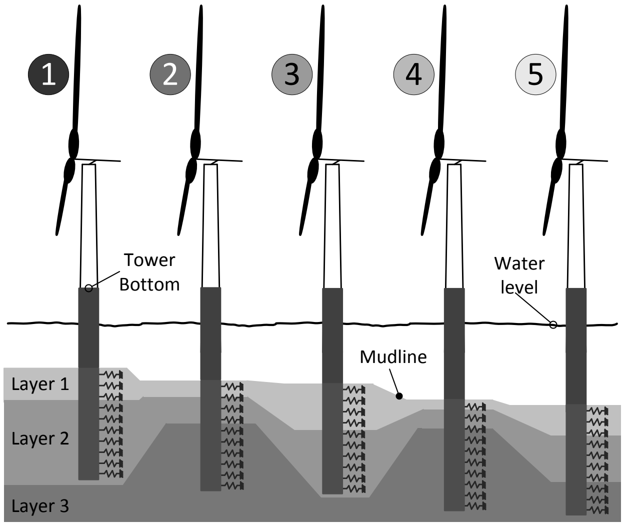

Fig. 1. The five OWTs of this study with different soil conditions and water depth

In order to limit the scope of the study, the support structures are not optimized for each position (although feasible in practice). Hence, the dimensions (diameter, wall thickness) of monopile and tower are the same for each of the five OWTs and correspond to the original OWT used within the OC3 project. It was verified, however, that the first natural frequencies of all turbines are in the allowed soft-stiff region between rotor frequency (1P) and blade passing frequency (3P). Table 1 presents the water depth and first natural frequencies for each position.

2.2. Soil conditions

A soil profile with up to three layers of sand was used in the study. The soil conditions and water depth for each position are illustrated in Fig. 1. The lengths of the soil layers differ between positions. It is assumed, however, that the soil parameters of each layer are identical within the wind farm. Soil parameters are presented in Table 2. These were adapted from the OC3 project Phase II [7]. For position 2 and 3 only two sand layers (layer 1 and 2) are used.

The soil-pile interaction is modelled with lateral springs distributed along the pile with 1m spacing. The springs are uncoupled and their stiffness is based on the nonlinear API *p-y* model for sand [9]. More details on the distributed spring model and the calculation of the spring stiffness can be found in [10].

Table 2. Parameters and properties for soil profile. Reference values are listed for k_{ref} initial modulus of subgrade reaction, ϕ'_{ref} angle of internal friction, γ'_{ref} effective unit weight.

Layer	k_{ref}	ϕ'_{ref}	γ'_{ref}	Pos. 1	Pos. 2	Pos. 3	Pos. 4	Pos. 5
Layer 1 (sand)	16287 kN/m^3	33.0º	10 kN/m^3	0-10m	0-5m	0-15m	0-2m	0-10m
Layer 2 (sand)	24430 kN/m^3	35.0º	10 kN/m^3	10-36m	5-14m	15-36m	2-8m	10-25m
Layer 3 (sand)	35288 kN/m^3	38.5º	10 kN/m^3	-	14-36m	-	8m-36m	25-36m

2.3. Wind and wave conditions

Wind and wave conditions were taken from the UpWind Design Basis [11]. According to this design basis, wind-wave scatter diagrams are reduced into several load cases. Each load case consists of a mean wind speed, corresponding lumped sea states, and a probability of occurrence. For this study 14 load cases that cover the design load cases 1.2 (power production) and 6.4 (idling) (c.f. [12]) are selected. Table 3 presents the environmental data used for this study. Wind and waves are taken as aligned and unidirectional over the entire lifetime. Irregular wave time series were created from JONSWAP wave spectra with significant wave heights and peak periods stated in Table 3. The cut-off frequencies were chosen to cover a frequency range from 0.5 Hz to 2 Hz.

Table 3. Environmental data and corresponding frequency of occurrence for the load cases performed in this study.

Load Case	Mean wind speed – free stream [m/s]	Turbulence Intensity [%]	Significant wave height [m]	Peak period [s]	Probability of occurrence [-]	Design Situation
1	2	15.1	1.07	6.03	0.06071	Idling
2	4	11.6	1.10	5.88	0.08911	Power production
3	6	9.85	1.18	5.76	0.14048	
4	8	8.76	1.31	5.67	0.13923	
5	10	7.99	1.48	5.74	0.14654	
6	12	7.40	1.70	5.88	0.14272	
7	14	6.93	1.91	6.07	0.08381	
8	16	6.55	2.19	6.37	0.08316	
9	18	6.22	2.47	6.71	0.04186	
10	20	5.94	2.76	6.99	0.03480	
11	22	5.70	3.09	7.40	0.01534	
12	24	5.49	3.42	7.80	0.00974	
13	26	5.30	3.76	8.14	0.00510	Idling
14	28	5.13	4.17	8.49	0.00202	Idling

Wind turbines located within an offshore wind farm are exposed to wakes from neighboring turbines. Wakes cause a reduction of wind velocity and an increase of turbulence intensity compared to free stream conditions. The Frandsen wake model [13] was used to account for wake effects. In this model, wake velocity deficits and turbulence intensities depend on thrust coefficient, rotor area, and distance and number of turbines in a row.

Fig. 2 (b) shows the location of the five wind turbines within the offshore wind farm. The number of turbines considered as neighbors in the Frandsen wake model are shown in Fig. 2 (a). As can be seen from Fig. 2 (a), the wake model accounts for the distribution of wind directions. However, the wind direction distribution is not considered in the load simulation (see Chapter 3). The turbines have a spacing of seven times the rotor diameter. The turbulent wind files – location-specific for every turbine position in the wind farm – were generated with the stochastic, full-field, turbulence simulator TurbSim (Version 1.06.00, NREL, Golden, Colorado).

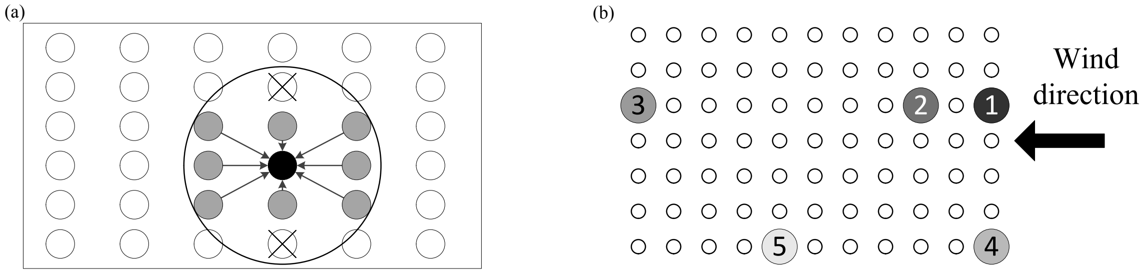

Fig. 2. (a) Turbines taken into account as neighboring turbines in the Frandsen wake model. (b) Turbine positions within a generic wind farm.

2.4. Corrosion

Monopiles are made out of steel and are situated in aggressive offshore environments. Parts of the support structure temporarily or permanently exposed to salt water and oxygen are threatened by corrosion. Corrosion reduces the fatigue resistant of steel which is represented in the application of different SN-curves for cathodic protection and free corrosion [14]. To minimize support structure dimensions corrosion protection is applied as much as practically possible. The submerged part of the monopile is typically protected by cathodic protection and coating in recent projects. The coating service life is assumed to be 15-20 years. The durability of the cathodic protection system is designed specifically for the project time so that free corrosion is prevented. In the study, the design case assumes full corrosion protection. Consequently, the SN-curve for “cathodic protection” is applied for 20 years.

3. Design and fatigue reassessment

This study consists of two steps. First, fatigue loading is assessed using the numerical models combined with the original environmental data from the UpWind Design Basis (cf. Section 2). This procedure is equivalent to the design phase of a real offshore wind farm but largely simplified (e.g. only 14 load cases, unidirectionality, no extreme load cases, no design optimization). The second step is a fatigue reassessment after the offshore wind farm has been in operation for several years. It is assumed that measurement data from operation has shown that environmental and operational conditions differ from design assumptions. Fatigue reassessment is a rerun of design simulations with updated environmental data and structural models as shown in [1]. In this study, only changes in environmental and operational conditions are addressed while structural models are unchanged from design.

3.1. Load simulations

The flexible multibody simulation tool Fedem Windpower (Version R7.2, Fedem Technology AS, Trondheim) was used to perform the load analysis of the OWT in the time domain. Fedem Windpower allows for an integrated dynamic analysis of the OWT under combined aerodynamic and hydrodynamic loads. Simulations were performed for operational and idling load situations in accordance with current standards [13], as stated in Table 3. Each load case was performed for a duration of 1 hour excluding transients.

The time series of fore-aft bending moments at tower bottom (Fig. 1) are used for fatigue assessment. Rainflow-counting was applied to determine the number of cycles, N, and the corresponding load amplitudes, S [15]. Fatigue loads are compared between design and reassessment using the surrogate parameter "equivalent fatigue load" (EFL). EFLs are the constant-amplitude load ranges that cause an equivalent amount of damage as the original variable-amplitude load time series at a reference number of cycles N_{ref} (cf. Equation 1). Here, the reference number of cycles is 10^6, S_i is the load range amplitude at cycle i, and m is a material parameter (here $m=4$).

$$EFL_{LC} = \left(\sum_{i=1}^{N} \frac{S_i^m}{N_{ref}} \right)^{\frac{1}{m}} \tag{1}$$

Equation 2 is used in order to obtain a total EFL. The EFLs for each out of the 14 load cases are weighted with the corresponding probability of occurrences, f_{LC}, (cf. Table 3) and summed up in order to obtain a total EFL value.

$$EFL_{Total} = \left(\sum_{LC=1}^{14} f_{LC} \cdot EFL_{LC}{}^{m} \right)^{\frac{1}{m}} \tag{2}$$

3.2. Parameters for fatigue reassessment

In a real project, parameters used in fatigue reassessment would be acquired from measurements during the operational phase of the offshore wind farm. Parameters in this study are varied according to a previous example (cf. [1]) as publically available data are lacking. Table 4 presents an upper and lower bound of each parameter compared to their design value.

Table 4. Parameter variations following Ziegler & Muskulus [1]. Turbulence intensity, significant wave height, and wave peak period depend on the mean wind speed and significant wave height, respectively (c.f. Table 3).

Parameter		Unit	Lower bound	Design	Upper bound
Mean wind speed	v_w	[m/s]	9.6	10	10.4
Turbulence intensity	TI	[-]	0.95 $f_1(v_w)$	$f_1(v_w)$	1.05 $f_1(v_w)$
Significant wave height	H_s	[m]	0.95 $f_2(v_w)$	$f_2(v_w)$	1.05 $f_2(v_w)$
Wave peak period	T_P	[s]	0.95 $f_3(H_s)$	$f_3(H_s)$	1.05 $f_3(H_s)$
Corrosion		[years]	0	0	10
Turbine availability		[%]	80	100	100

Wind speeds and turbulence intensity are location-specific for each turbine in the wind farm. Turbulence intensities are varied by 5% compared to the location-specific design value reflecting uncertainty in wake models. Further details on the variation of parameters and sources can be found in [1]. Each parameter is varied separately, while the remaining parameters were kept constant. This neglects potential interaction effects as discussed in [1].

4. Results and discussion

4.1. Design process

Fig. 3 (a) shows the EFLs for each load case which are weighted with the probability of occurrence. EFLs from idling load cases are usually larger due to missing aerodynamic damping from the turning rotor. However, the probability of occurrence for wind speeds outside the operational wind speeds are typically smaller thereby leading to a smaller contribution to the total EFL. This is not the case for the idling case at 2 m/s (load case 1), where the probability of occurrence is similar to some operational load cases (cf. Table 3) and significantly higher than the remaining idling cases (load case 13 and 14). Hence, load case 1 contributes to a similar or even larger amount to the total EFL as an operational load cases. Generally, the idling cases contribute with around 20% to the total EFL (see Fig. 3 (b)). The figure also shows that EFLs increase for deeper water and lower natural frequency of the support structure, which is in agreement to previous studies [4].

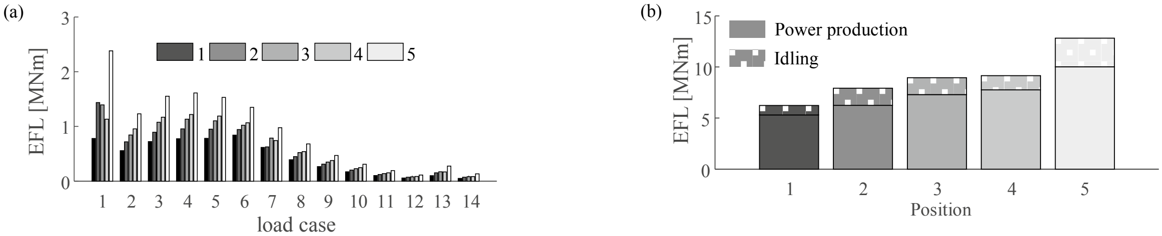

Fig. 3. (a) EFL for each load case weighted with the probability of occurrence. The numbers 1-5 label the five turbine positions in the wind farm. (b) Total EFL combined from all load cases for each position in the design case.

4.2. Reassessment

The results for fatigue reassessment considering changes in wind conditions are shown in Fig. 4. Both, mean wind speed and turbulence intensity, have only a small effect on the EFLs for all positions. This is in contrast to [1], where wind parameters dominated wave parameters for the monopile in 20m water depth. In [1] the monopile was modelled with a rigid foundation neglecting soil-structure interactions. As a result, the first natural frequency was 16% higher compared to position 2 in this study. This led to less hydrodynamic excitation here as the first natural frequency is further away from the wave peak frequency.

Fig. 5 shows the influence of hydrodynamic parameters. At the same position, a variation of the significant wave height causes an identical upward and downward change of EFLs. This linearity is confirmed by previous publications [4], [6]. In addition, the behaviour among the positions is similar. For example, 5% higher H_S causes an increase of EFLs of 4.7% at position 1 and 6.0% at position 5. The similarity is even larger for the wave peak period. For example, 5% lower T_P causes an increase of EFL between 7.6% (position 1) and 8.2% (position 2). These results suggest that an extrapolation from one reassessment position to the remaining turbines in the wind farm might be feasible. However, note that a 5% variation of parameters is small. The behaviour of loads at different position is expected to diverge for larger changes of the parameters. This is in line with Ziegler et al [3] who showed that hydrodynamic loading changed approximately linear within 5-10% of variation of wave parameters.

The results for reduced availability are presented in Fig. 6 (a), where the OWT spent 20% of the time in idling. The system's damping is small without aerodynamic damping, thus, EFLs increase. Aerodynamic damping can be more than 10%, while the damping ratio for structural damping is only 0.3% in this study. There is no clear trend of the behaviour of EFLs between the turbine positions. This originates from an overlaying effect of water depth and soil.

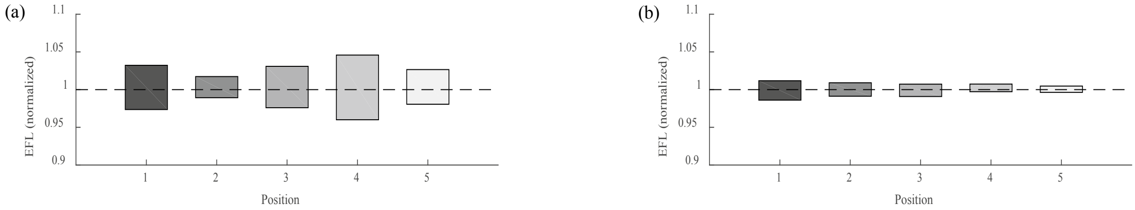

Fig. 4. Total EFL at each position for (a) v_w +/-4% and (b) TI +/-5%. The results are normalized to the design case. An increase in mean wind speed as well as turbulence intensity results in an increase of the total EFL

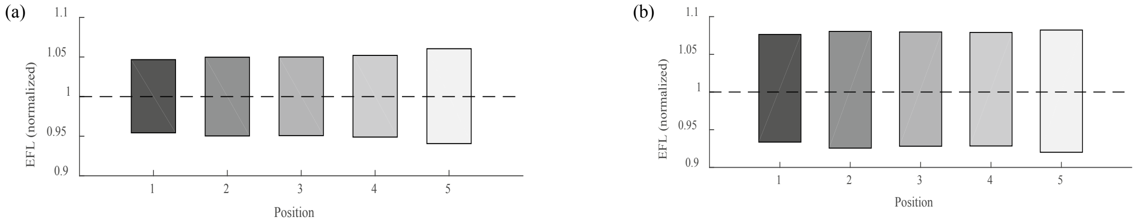

Fig. 5. Total EFL at each position for (a) H_s +/-5% and (b) T_p +/-5%. The results are normalized to the design case. An increase in significant wave height results in an increase of the total EFL, while an increase in wave peak period leads to a decrease of the total EFL.

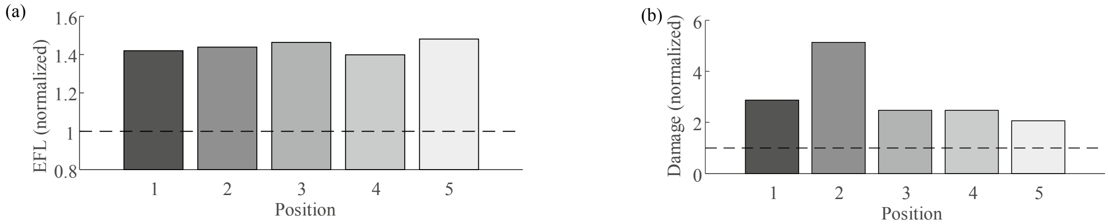

Fig. 6 (a). Total EFL at each position for 80% availability. (b) Fatigue damage at each position for free corrosion after 10 years. The results are normalized to the design case.

An increase in water depth makes hydrodynamic loading more important – which is the driving load for turbine idling. When the monopile is clamped at mudline (rigid foundation), the EFLs from idling load cases increase with the water depth (not shown). On the other hand, soil stiffness affects the results. At position 4, the third soil layer is predominant which has higher stiffness properties. This may explain that EFLs at position 4 increase less compared to position 2 and 3. It can already be observed in Fig. 3 (a), that the EFLs from idling load cases for position 4 are slightly smaller than for position 2 and 3. An increase of idling during the operational lifetime of the turbine, as it is done for the reduced availability assumption, leads therefore to a more significant increase in the total EFL for position 2 and 3 compared to position 4. This effect is less important for operational load cases with high damping.

The load simulations are unchanged for the parameter corrosion. The fatigue damage caused during the time spent in corrosion (10 years) was calculated with Palmgren-Miner rule of linear damage accumulation and the SN-curve for "free corrosion" [14]. The SN-curve for "cathodic protection" was applied to calculate the damage for the corrosion-free time (previous 10 years). The total damage is calculated by adding the damage caused in the time of free corrosion and the time in "cathodic protection". The changes in fatigue damage in relation to the design case where the "cathodic protection" SN-curve is applied for the total lifetime of 20 years are shown in Fig. 6 (b). The "free corrosion" SN-curve has a slope of $m=3$ for all load amplitudes, while the "cathodic protection" SN-curve has a slope of $m=3$ (for stress ranges >52.63MPa) and $m=5$ (for stress ranges <52.63MPa) [14]. Hence, the effect of applying the "free corrosion" SN-curve is stronger for stress time series with the majority of stress cycles in the range below 52.63 MPa. This explains the different behaviour regarding the increase in fatigue damage among the five positions. Position 1, 3, 4, and 5 have the majority of stress cycles above 52.63MPa and the increase in fatigue damage is, therefore, less significant as it is for Position 2 where more stress cycles are counted below 52.63MPa.

In contrast to the results from wind and wave parameters, there is no similarity of the behaviour between the positions. An extrapolation from one reassessment to the other positions would hardly be possible without individual analysis. Nevertheless, in all parameter studies the highest loaded location (position 5) and lowest loaded location (position 1) stayed the same, except for the free corrosion case where the highest loads were observed at position 2 due to the significant increase in fatigue damage as explained in the paragraph above.

5. Conclusion

The study presented in this paper compares fatigue assessments in the design phase with fatigue reassessments performed towards the end of the design lifetime, where environmental data from the service lifetime of the turbine can be used. Several environmental parameters causing differences in aerodynamic and hydrodynamic loading were modified. Results indicate that it can be possible to extrapolate fatigue reassessment results from selected design positions to the entire wind farm under the assumptions of this study. Changes in environmental and operational conditions were assumed to be small and independent of each other, which will differ in reality. Furthermore, it was shown that an extrapolation is not feasible for each parameter (e.g. free corrosion). Consequently, safety factors may be needed to compensate for model uncertainty introduced through extrapolation of fatigue reassessment. In this study, the highest loaded position remains the same in all considered parameter variations. This is an important observation for a decision about lifetime extension for larger offshore wind farms as a redesign of all turbines might not be cost-effective. This trend, however, has to be verified in order to be able to make a conservative judgement. Further research should evaluate if the observed behaviour is still valid for a full design basis and designs that are optimized for their position. Future studies should also consider larger changes in environmental conditions and investigate for which parameters an extrapolation is possible within the fatigue reassessment. In addition, there is still a missing link between numerical fatigue reassessments and on-site measurements.

Acknowledgements

Support by the Norwegian Research Centre for Offshore Wind Technology (NOWITECH FME, Research Council of Norway, contract no. 193823) is gratefully acknowledged. In particular we thank Fedem Technology AS for support. This project has also received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642108. Sincere thanks are also given to Lars Einar Sørensen Stieng (NTNU) for kindly providing his Matlab script for *p-y* curve calculation.

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