APPROACH TO WIND WAVE CORRELATION IN COUPLED ANALYSIS OF OFFSHORE WTG SUBSTRUCTURES

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Offshore wind turbines need to be designed to withstand the expected environmental conditions throughout their design life, typically 25 years. It is current practice to perform structural analysis considering both wind and wave effects using time domain procedures, which can be very lengthy. Simplification of complex wind/wave relationships (speed, height, period and directionality) therefore needs to be undertaken in a realistic manner. Normally, the wind conditions are analysed in detail by the turbine supplier, however, the wave model is simplified by definition of sea states as a function of wind speed. Directionality of the waves is typically represented by misalignment relative to the wind. From wave loads perspective this approach might not accurately reflect the real wave climate at the site and hence wave fatigue damage may be estimated inadequately. A technique has been developed for calibrating the above simplified sea state definition using spectral fatigue analysis methods. Typical results are presented showing calibrated wind-wave data relations. The resultant calibrated wave fatigue conditions are then suitable for combination with wind conditions and will yield more accurate combined fatigue lives. This will allow effective structural designs of the substructure for wind turbines under combined wind and wave loading effects.

Keywords: *offshore wind, wind/wave correlation, fatigue limit state, spectral fatigue, calibration*

1. INTRODUCTION

Offshore wind turbines need to be designed to withstand the expected wind and wave environmental conditions throughout their design life (typically 25 years). Due to the significant dynamic response, one of the requirements of an efficient design process is to simulate the complete system including the tower and foundation for strength and fatigue conditions. It is current practice to perform structural analysis using a dynamic time domain procedures, which can be very time consuming.

Simplification of wind/wave relationships is important to reduce the total analysis times to practical levels. However, such simplification needs to be undertaken without loss of accuracy. At any given site, wind and waves are intricately related to each other in terms of their speed, height, periods and directions. Establishing a realistic correlation between the wind and wave conditions is hence a pre-requisite for any coupled analysis process of the turbine and substructure/foundation.

Traditionally, the various wind conditions are analysed by the turbine supplier in detail, covering expected magnitudes and directions and defining their probability of occurrence over the wind turbine design life. However, the superposition of wave loading is also important, not just its varying magnitude but also its alignment or misalignment relative to the wind.

Faced with such potential conservatism, it is normal to simplify the wave model by a specification of the sea states in order to be a function of wind speed. Directionality of the waves is typically represented by its misalignment relative to the wind.

This approach results in the probability of wave magnitude and direction being subservient to the wind probability. The concern is that the resulting wave climate may not accurately reflect the real wave climate of the site and consequently, wave fatigue damage may be misrepresented.

A technique has been developed for calibrating the above simplified sea state definition using a spectral fatigue analysis method. The technique that will be presented and discussed herein has been successfully applied to various commercial wind farm substructure design projects, allowing a robust structural design of the foundation of wind turbines under combined wind and wave loading effects.

2. DATA COMPLEXITY

A large number of wind-wave combinations exist for any particular site. Available metocean information is normally used to characterize the site's environmental conditions. This information normally comes in the form of either raw hindcast data listing the chronological occurrences of wind-wave conditions, or post-processed wind and wave roses and wave scatter tables as illustrated below in Figures 1, 2 and 3 for a generic site.

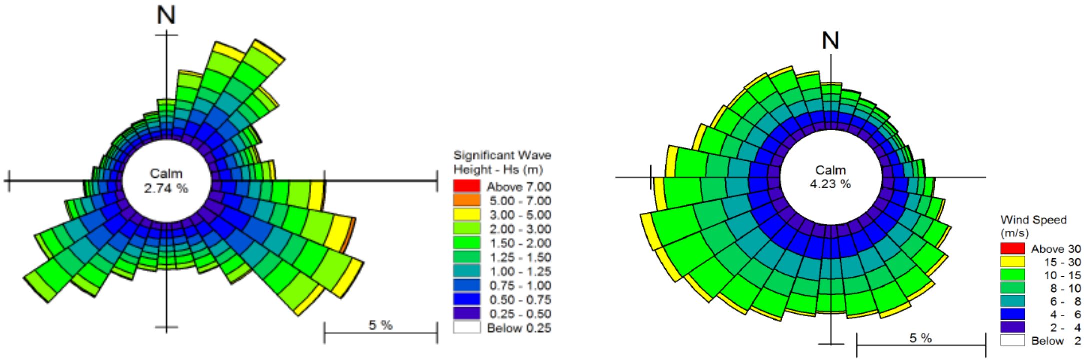

Figure 1. Wind and Wave Roses

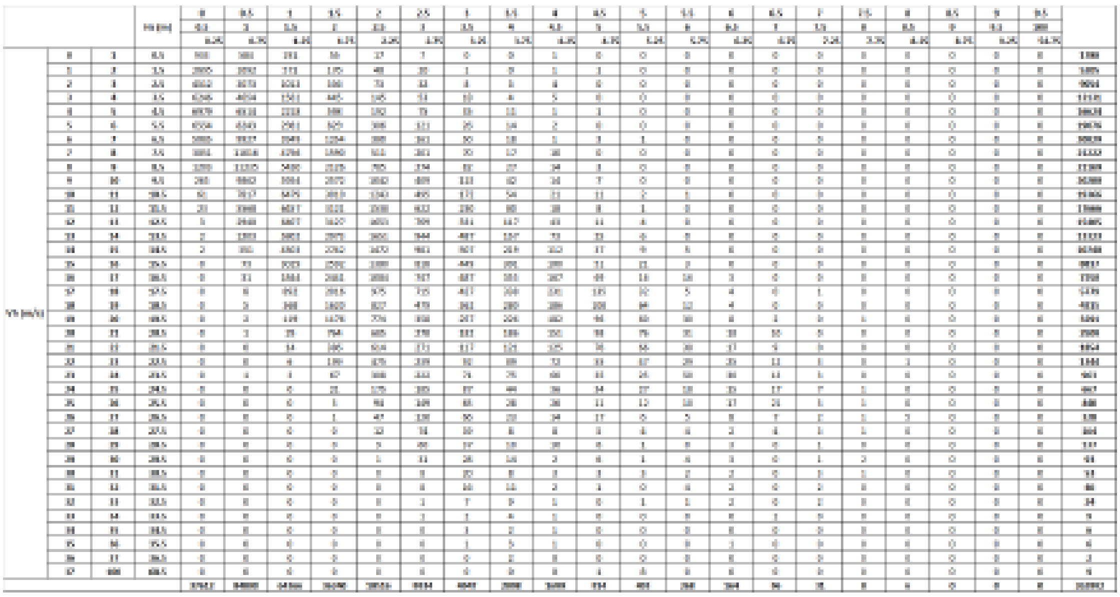

Figure 2. Wind Speed (v) vs Significant Wave Height (Hs)

These comprehensive datasets form the basis for any site specific wind-wave correlation, characterizing the existing climate conditions and providing the necessary probabilistic information required.

The resolution of the metocean data also has an influence on the correlation proposed. For the data presented in this paper, wind speeds are lumped in 1m/s bins, whilst the significant wave heights are lumped in 0.5m bins, and the wave periods are accumulated in 1second bins.

3. ANALYSIS REQUIREMENTS

Offshore wind turbines are subject to complex loading conditions. The structural response is highly dynamic and it depends on a large number of factors interrelated to each other. In order to obtain certification on a site-specific substructure design, a simulation that accounts for the coupled excitation and response of the complete system, including turbine and substructure, is required. This analysis, commonly known as coupled- analysis, takes into account the following factors as a minimum: influence of mean wind and turbulence, aerodynamics, structural dynamics, control systems, waves, currents, and hydrodynamics [1].

			Mean Zero-Crossing Wave Period (s)													
			[0,1)	[1,2)	[2,3)	[3,4)	[4,5)	[5,6)	[6,7)	[7,8)	[8,9)	[9,10)	[10,11)	[11,12)	[12,13)	
Significant Wave Height			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	All Wave Periods
≥0,	<0.5	0.25	2	8102	24302	4385	810	11	0	0	0	0	0	0	0	37612
≥0.5,	<1	0.75	0	1	34761	38278	7904	3189	657	10	0	0	0	0	0	84800
≥1,	<1.5	1.25	0	0	33	40191	16293	4581	2739	522	7	0	0	0	0	64366
≥1.5,	<2	1.75	0	0	0	3947	23726	5436	1787	1260	82	2	0	0	0	36240
≥2,	<2.5	2.25	0	0	0	3	7406	8111	1776	831	368	21	0	0	0	18516
≥2.5,	<3	2.75	0	0	0	0	822	5576	2314	717	452	53	0	0	0	9934
≥3,	<3.5	3.25	0	0	0	0	38	1320	2652	609	185	142	1	0	0	4947
≥3.5,	<4	3.75	0	0	0	0	0	165	1678	792	172	83	8	0	0	2898
≥4,	<4.5	4.25	0	0	0	0	0	7	470	980	181	39	22	0	0	1699
≥4.5,	<5	4.75	0	0	0	0	0	0	56	573	240	36	9	0	0	914
≥5,	<5.5	5.25	0	0	0	0	0	0	11	203	251	26	2	0	0	493
≥5.5,	<6	5.75	0	0	0	0	0	0	0	41	196	30	1	0	0	268
≥6,	<6.5	6.25	0	0	0	0	0	0	0	13	111	39	1	0	0	164
≥6.5,	<7	6.75	0	0	0	0	0	0	0	0	42	54	0	0	0	96
≥7,	<7.5	7.25	0	0	0	0	0	0	0	0	9	21	1	0	0	31
≥7.5,	<8	7.75	0	0	0	0	0	0	0	0	0	7	1	0	0	8
≥8,	<8.5	8.25	0	0	0	0	0	0	0	0	0	2	4	0	0	6
≥8.5,	<9	8.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥9,	<9.5	9.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥9.5		9.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		All Wave Heights:	2	8103	59096	86804	56999	28396	14140	6551	2296	555	50	0	0	262992

Figure 3. Significant Wave Height (Hs) vs Zero Crossing Period (Tz) Scatter Tables

There are different methodologies for completing a coupled wind-wave analysis between Wind Turbine Generator (WTG) manufacturers and substructure designers, mainly distinguished by: i) sequential; and ii) fully integrated coupled analysis. In both cases, wind and wave loading needs to be simulated to represent the different conditions expected to occur during the design life of the structure.

The load cases to be analysed are defined for both fatigue and ultimate limit state conditions, for example in accordance with IEC 61400 [2].

This paper will focus on the fatigue limit state only. The analysed fatigue load cases need to accurately represent all expected load conditions to be experienced by the turbine and substructure during its design life so that a representative fatigue life can be obtained.

As defined in DNVGL-ST-0126 [3], the following load conditions must be considered as contributing to the foundation fatigue loading: normal power production, WTG parked idling, WTG idling, waiting for commissioning and decommissioning, WTG Start-up, WTG Shut down as well as fault and loss of grid scenarios. These turbine operational conditions need to be combined with concurrent environmental loading in order to represent the complete load history.

All the potential combinations of wind speed, wind direction and sea state conditions are to be considered with every combination having an associated probability of occurrence during the design life of the structure. The above leads to a very large number of load conditions for fatigue alone.

Additionally, each load case is normally analysed as a 10min simulation in time steps of 0.02 to 0.04s resulting in a total of 15000 or more time steps per simulation. Therefore, the analysis time becomes very lengthy and not practical in commercial projects for too many load cases.

Some simplification in the number of simulations is therefore required. There are various possibilities to achieve this such as limiting the number of wind speeds analysed, limiting the number of wind and wave directions considered etc. Due to the natural correlation between site specific wind and wave climates (wind speeds drive wave heights), a reasonable solution is to simplify the number of wind and wave combinations to be analysed using suitable wind/wave relationships.

3.1. DIFFERENT TRADITIONAL APPROACHES TO WIND WAVE CORRELATION

A number of different options exist for correlating wind and wave loading for coupled fatigue analysis. The advantages and limitations of the main approaches are discussed below:

- Approach 1: Analyse all possible combinations of existing wind and wave loading. This approach results in most accurate results. However, the required analysis time is too lengthy and impractical as there are many combinations of wind speed and wave height for even a single direction (see Figure 2).
- Approach 2: Correlate the wind condition to the sea state that has the same probability of occurrence. This approach accurately represents the wave climate of the site and analysis times are reduced to practical levels. However, the analysed combinations of wind and wave loading are not necessarily related or realistic. These combinations may introduce artificially higher or lower loading due to dynamic effects which can affect the resulting combined fatigue life of the structure.
- Approach 3: Correlate the wind condition to a corresponding sea state using polynomial fits based on site specific scatter diagrams. This approach, whilst proposing realistic combinations of wind and wave conditions and reducing analysis times, might result in a wave climate that over or under estimates the underlying probabilities of the waves analysed. Consequently, the wave fatigue damage on the structure might be over or under estimated.
- Approach 4: This approach is based on approach 3 but additionally calibrates the polynomial relationships to ensure that the simplified wave climate produces the expected site specific wave fatigue loading.

Approach 4 constitutes Atkins preferred approach and will be explained in more detail in Section 4 below.

4. ATKINS WIND WAVE CORRELATION APPROACH

The list of fatigue load cases to be analysed is normally created by the WTG manufacturer and constitutes an input to the wind wave calibration. The incoming wind conditions are normally analysed in detail, covering expected magnitudes, directions and probabilities. The wave climate superimposed on these conditions are then typically defined by the substructure designer.

Based on the environmental conditions for the site, a simplification of possible wind/wave combinations is proposed, consistent with the requirements previously listed. This correlation is based on two independent simplifications as explained in sections 4.1 and 4.2 below.

4.1. WIND-WAVE RELATIONSHIPS

To simplify the number of cases considered, only one sea state (Significant Wave Height (Hs), Mean Wave Zero Up-Crossing Period (Tz) / Peak Wave Period (Tp)) is defined per direction for each corresponding wind speed. In this way, the number of possible wind/wave combinations is significantly reduced.

The first step is to define polynomial relationships between the wind speed and the significant wave height (Hs vs Mean wind speed at hub height (Vw)), and between significant wave height and peak or zero-crossing period (Tp vs Hs / Tz vs Hs), to obtain the corresponding sea state for each wind speed and wave direction. The reason for considering Tp or Tz is that different software uses different values to define seastates.

These correlation functions are based on the site specific scatter diagrams approximated by a 5th order polynomial fit at a determined percentage of non-exceedance as can be seen below in Figures 4 and 5. It is within the scope of the calibration exercise (see later) to obtain the appropriate percentage of non-exceedance to be used in order to get the best fit to the expected wave climate.

Relating Hs to wind speed (V) in this way results in a probability distribution of Hs that is subservient to the wind probability distribution. This is not necessarily the same as the distribution of Hs given in the scatter diagrams. It is therefore necessary to check and calibrate the wave load history generated this way to ensure that it provides a suitable description of the true long term wave climate. This is described in Section 5.

It must be highlighted that the resulting functions are highly sensitive to the accuracy of the coefficients used (see Figure 6). Therefore, it is very important to use exact numbers, with minimal rounding, when calculating Hs, Tp and Tz from these relationships. Care should be taken to ensure that the polynomials actually represent trends, particularly at higher wind speeds where the data is more infrequent and therefore less predictable.

Hs			Mean Zero-Crossing Wave Period (s) — Tz												
			[0,1)	[1,2)	[2,3)	[3,4)	[4,5)	[5,6)	[6,7)	[7,8)	[8,9)	[9,10)	[10,11)	[11,12)	[12,13)
Significant Wave Height			0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
≥0,	<0.5	0.25	0	0	2.440375	0	0	0	0	0	0	0	0	0	0
≥0.5,	<1	0.75	0	0	0	3.19954	0	0	0	0	0	0	0	0	0
≥1,	<1.5	1.25	0	0	0	3.79993	0	0	0	0	0	0	0	0	0
≥1.5,	<2	1.75	0	0	0	0	4.597362	0	0	0	0	0	0	0	0
≥2,	<2.5	2.25	0	0	0	0	0	5.227962	0	0	0	0	0	0	0
≥2.5,	<3	2.75	0	0	0	0	0	5.743364	0	0	0	0	0	0	0
≥3,	<3.5	3.25	0	0	0	0	0	0	6.420626	0	0	0	0	0	0
≥3.5,	<4	3.75	0	0	0	0	0	0	6.765197	0	0	0	0	0	0
≥4,	<4.5	4.25	0	0	0	0	0	0	0	7.380102	0	0	0	0	0
≥4.5,	<5	4.75	0	0	0	0	0	0	0	7.699825	0	0	0	0	0
≥5,	<5.5	5.25	0	0	0	0	0	0	0	0	8.129482	0	0	0	0
≥5.5,	<6	5.75	0	0	0	0	0	0	0	0	8.47449	0	0	0	0
≥6,	<6.5	6.25	0	0	0	0	0	0	0	0	8.621622	0	0	0	0
≥6.5,	<7	6.75	0	0	0	0	0	0	0	0	0	9.111111	0	0	0
≥7,	<7.5	7.25	0	0	0	0	0	0	0	0	0	9.309524	0	0	0
≥7.5,	<8	7.75	0	0	0	0	0	0	0	0	0	9.571429	0	0	0
≥8,	<8.5	8.25	0	0	0	0	0	0	0	0	0	0	10.25	0	0
≥8.5,	<9	8.75	0	0	0	0	0	0	0	0	0	0	0	0	0
≥9,	<9.5	9.25	0	0	0	0	0	0	0	0	0	0	0	0	0
≥9.5		9.75	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0		0	0	0	0	0	0	0	0	0

Figure 4. Hs vs Tz relationship at 50% percentage of non-exceedance

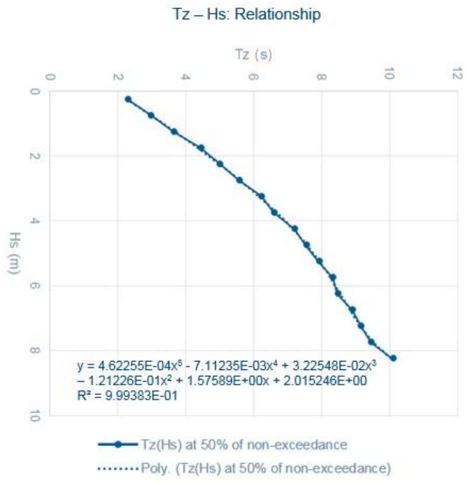

Figure 5. Polynomial fit for the Tz-Hs relationship at a 50% non-exceedance

4.2. DIRECTIONAL CORRELATION

The second part of the correlation process involves a directional simplification of all the possible wind/wave direction combinations. Relative wind-wave directionality is important particularly for monopiles, as aerodynamic to wave induced motions can vary significantly with misalignment.

In the analysis, wave direction is typically determined by offsetting the wind direction by a specified wind-wave misalignment.

As wind speeds and corresponding wave heights increase, the relative misalignment between wind and wave typically reduces. At high wind speeds, fully developed sea states are normally observed and therefore, wind and wave directions are found to be predominantly aligned. For these cases, little or no misalignment needs to be considered.

At lower wind speeds, a reduced number of misalignments is normally considered. Waves from opposing directions cause similar fatigue (because of the similar alternating loads at crests and troughs) and these may be lumped into one misalignment case.

The wind-wave relationships proposed in Section 4.1 are for a single direction. The relationships used where there is wind-wave misalignment are selected based on the wave direction. This is because the wave fetch to shore is found to be the most significant factor in these relationships.

A wave rose resulting from this simplified approach to wave definition can be created and is seen in Figure 7 for two different sites. The simplification proposed needs to be site specific, determined by the climate conditions and prevailing wave directions for the site.

The simplification of the wind/wave misalignment and the fact that the probability of the waves is dependent on the wind probability, results in a wave rose that is slightly different from, but representative of, the site specific rose. Once again, it must be reinforced that the correlation model needs to be calibrated (see Section 5) so that the wave load history generated provides a suitable description of the true long term wave climate of the site, for fatigue purposes.

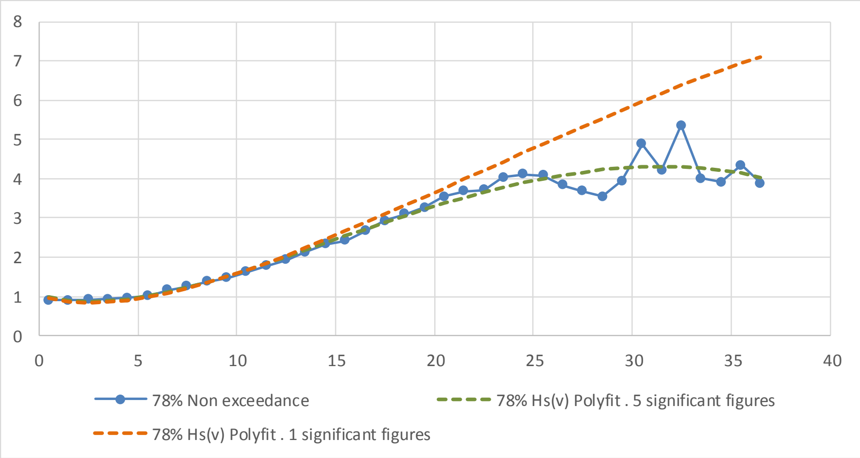

Figure 6. Polifit sensitivity to the number of significant figures used to define the coefficients

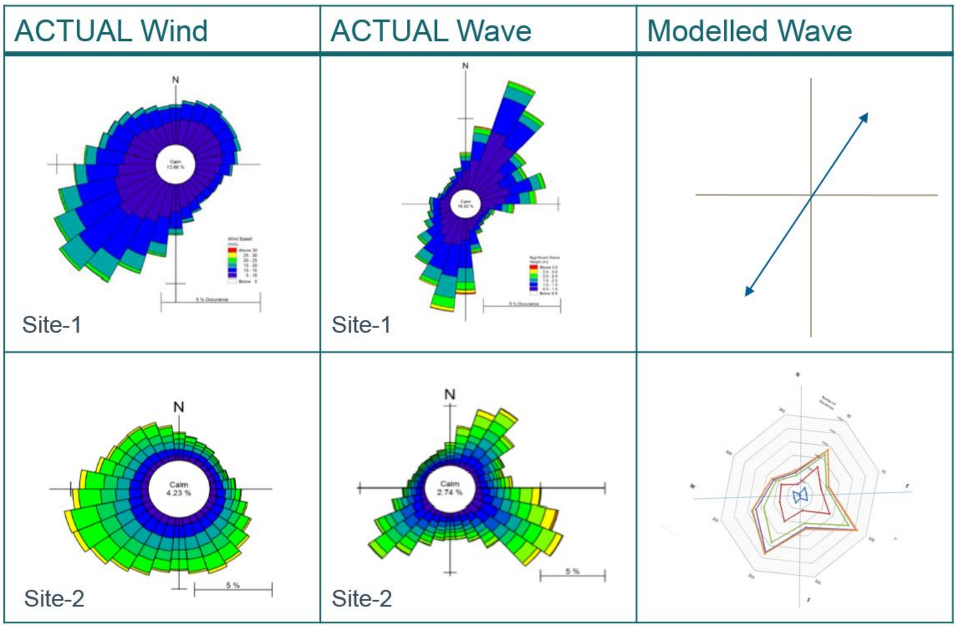

Figure 7. Directional Correlation

5. CALIBRATION OF WIND-WAVE RELATIONSHIPS

The correlation proposed in Section 4 above results in a wave climate that might not be fully reflective of the true wave climate of the site due to the probabilities of the waves being subservient to the probabilities of the wind.

The objective of the calibration exercise is to assess the accuracy of these relationships, and to compensate for any inaccuracy by calibration of the relationships.

As fatigue tends to be a governing load scenario for jacket and monopile substructure design, it is of great importance to undertake accurate analysis that does not significantly over or underestimate the fatigue lives of the structural members. Atkins calibration approach for achieving this is summarized in the diagram in Figure 8.

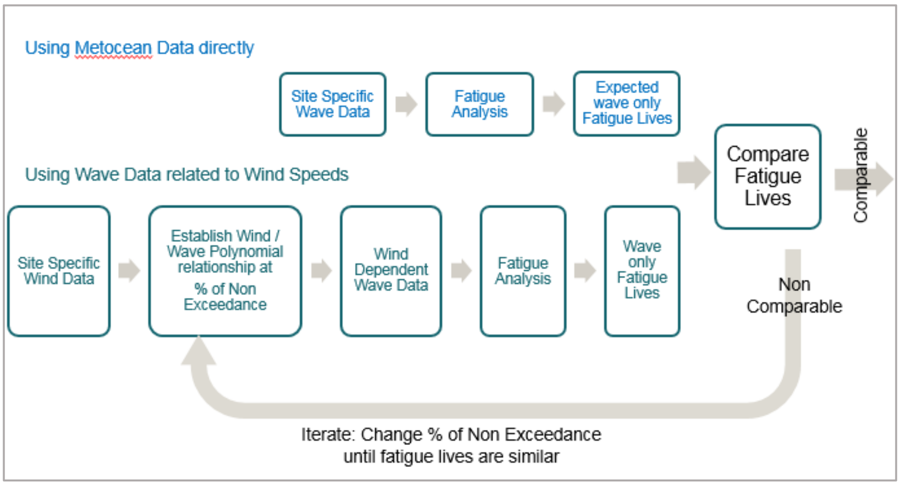

Figure 8. Atkins Wind-Wave calibration approach

The method adopted is to perform fatigue analysis of the WTG structure under wave loading only, using traditional spectral wave fatigue analysis methodologies [4]. A representative substructure model needs to be used for this purpose. This assessment compares:

- wave only fatigue using the full omni-directional wave scatter data from the Metocean Report
- wave only fatigue with wave probabilities and periods based on the associated probability of wind loading as derived from the proposed correlation (Section 4, above).

In this way, the underlying simplified wave fatigue loading being proposed for combination with wind fatigue load can be compared and calibrated against the expected wave conditions. The resultant calibrated wave fatigue conditions are then suitable for combination with wind fatigue and would be expected to give accurate combined fatigue lives.

In order to reach this outcome, an iterative trial and error process is followed. The fatigue lives from the two wave fatigue analyses are compared at different hot spots in the structure. The wind/wave polynomial relationships are then adjusted by changing the percentage non-exceedance used to define them (see Section 4.1). The analyses is then repeated until the fatigue live results are comparable.

Sensitivity studies based on the variation of the percentage non-exceedance for the difference relationships has shown the following:

- Hs vs Vw relationship: High values of significant wave height (given by high values of percentage non-exceedance of Hs for a given V) have a global effect on the structure, lowering the fatigue lives at every hot spot inspected on the structure.
- Tp vs Hs / Tz vs Hs relationships: Low values of wave period (given by lower values of percentage non-exceedance of Tz/Tp for a given Hs) give lower fatigue lives towards the top of the structure, relative to the bottom. This is expected, as these low period / steep waves will have high surface velocities, but will not be felt as much at depth as longer period waves, which will be more dominant for global effects.

Separately adjusting the relationships for Hs vs Vw and Tp or Tz vs Hs therefore offers a good degree of control over the calibration exercise.

6. SAMPLE CALIBRATION RESULTS

The calibration methodology described above has been applied to an example jacket structure, but may equally be used for monopiles, Gravity Base Structure, etc. In this case, a pre-piled, four-legged jacket substructure in 45m deep water has been subject to consideration.

The ASAS software system has been used to perform the spectral wave fatigue analyses. ASAS is a mature and extensively validated software package, and can perform all the necessary fatigue checks via the FATJACK program. FATJACK defines seastates using Tz, so only the Tz(Hs) relationship is presented here.

Fatigue lives were calculated at the different hot spots in the substructure in accordance to DNVGL-RP-0005 [5]. This included: fatigue checks on circumferential welds along the legs; checks at secondary attachments to the legs; tubular joints; circumferential welds on the braces.

Fatigue lives have been reported at the worst locations around the jacket at each specified vertical level. See Figure 9 for clarification of the notation used in the summary tables.

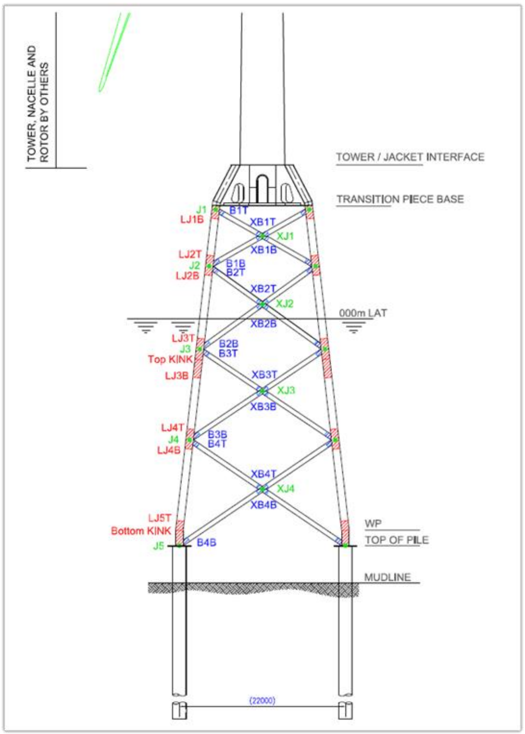

Figure 9. Joint Locations and notation for jacket fatigue analysis

6.1. MEAN FIT FATIGUE ANALYSIS RESULTS

As a starting point to the calibration exercise, a mean fit approach was used in the wave only fatigue analysis, setting a 50% non-exceedance for both the Hs(Vw) and Tz(Hs) relationships.

As it can be seen in Figure 10, the mean fit approach results in the probability of larger wave heights being under-predicted compared to the direct Metocean wave data. Consequently, the fatigue damage from the simplified set of waves is under predicted (see Figure 11). If this approach was used, there is a risk that the substructure would be under-designed with the consequential potential risk for fatigue failures during the design life of the substructure.

This illustrates the need to perform the proposed calibration exercise to correct this under-prediction.

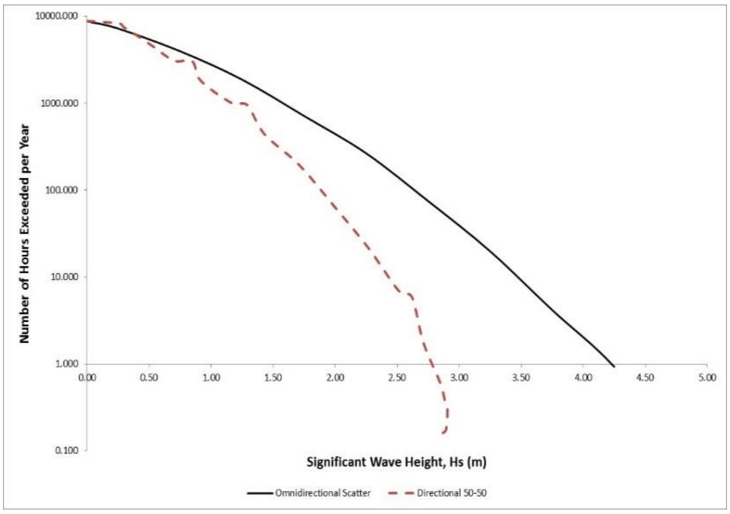

Figure 10. Significant wave height (Hs) exceedance plot for Mean Fit

Location on Jacket	Fatigue Life -Simplified approach Wave prob = f (Wind prob) PMOS 50-50 Position: Leg Cans	Leg Attachments	Joint	Braces
Bay 1- Y joint	N/A	N/A	N/A	N/A
Bay 1- X Joint			N/A	N/A
Bay 2-Top K-Joint	0.64	0.61	0.60	0.61
Bay 2 - X joint			0.49	0.52
Bay 3-Top K-Joint	0.58	0.60	0.58	0.63
X Joint - Bay 3			0.50	0.32
Bay 4-Top K-Joint	0.52	0.49	0.28	0.40
X Joint - Bay 4			0.25	0.28
Top of Leg Can	0.32			
Bay 4-Bottom K-Joint			0.58	0.27
Top of Pile		0.45		
Pile	0.34			

$$\text{Life Factor} = \frac{\text{Fatigue Life from Omnidirectional: Metocean } Waves}{\text{Fatigue Life from Mean Fit Calibration: Simplfied waves}}$$

Figure 11. Fatigue Life factors for mean fit approach

6.2. BEST FIT FATIGUE ANALYSIS RESULTS AND LIMITATION

An iterative approach has resulted in the best fit relationship between wind speed (Vw) and wave height and period (Hs and Tz) for wave loading only. Combined wind-wave fatigue would then be expected to give a better correlation because of the reduced reliance on the wave correlation.

The analysis has concluded that a 78%-40% combination is the optimum fit giving reasonably conservative fatigue lives throughout most of the jacket and piles.

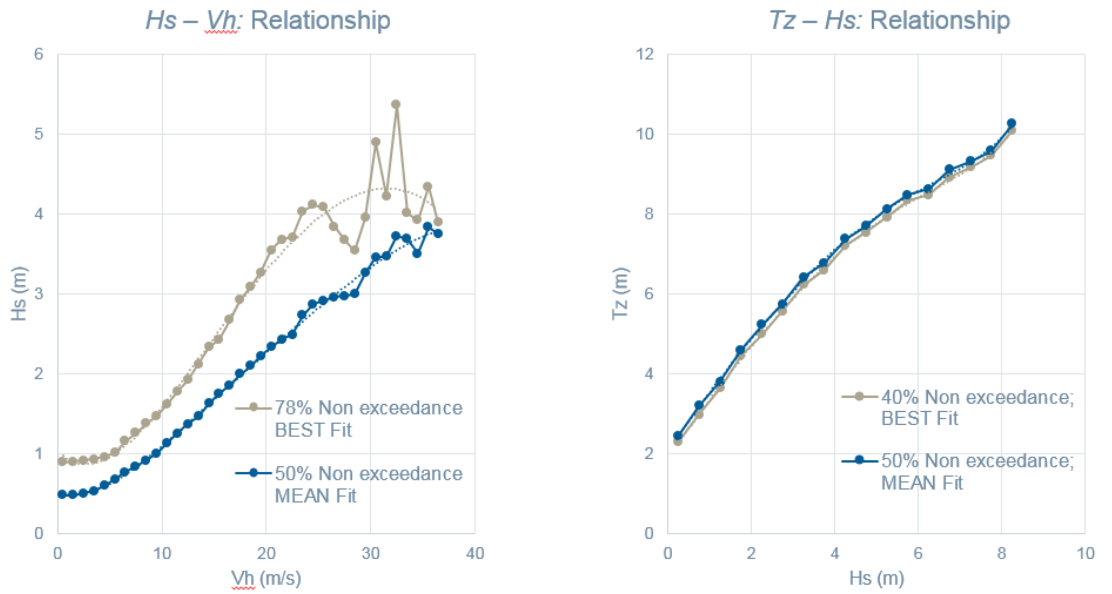

Figure 12. Polynomial relationships for mean fit and best fit calibration

The polynomial relationships for this case as well as for the mean fit (50%-50%) are shown in Figure 12. Only omnidirectional relationships are shown herein. However, similar relationships have been derived for the 8 directional sectors considered.

The updated exceedance plot in Figure 13 clearly shows how the best fit calibration proposed provides a much closer representation to the metocean wave height distribution. The occurrence of bigger waves is slightly under predicted whilst the occurrence of smaller waves is over predicted. Overall, these two effects compensate in a way that produce total fatigue damage similar to that caused by the true site specific wave climate.

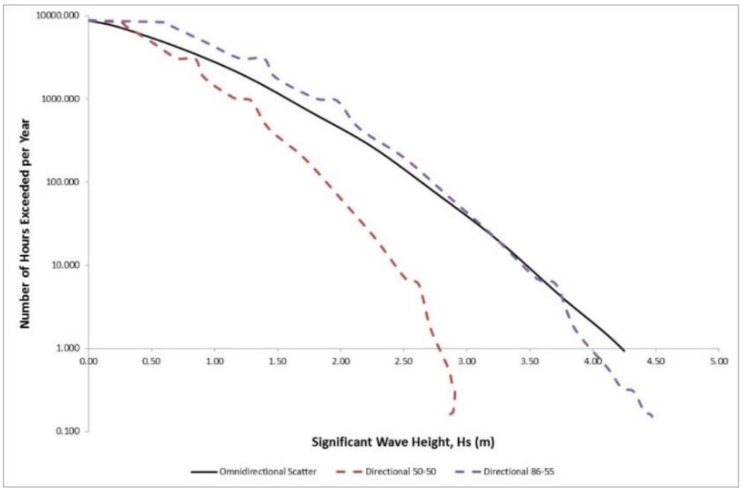

Figure 13. Significant wave height (Hs) exceedance plot for Best Fit

The fatigue life factors for the best fit analysis are shown in Figure 14. It is noted that three locations in the jacket show higher fatigue lives than those coming from the omnidirectional spectrum. Adjusting the percentages non-exceedance to correct these would be highly conservative for the rest of the substructure, so this is not advised. Care will need to be taken to ensure that these three locations have conservative fatigue lives in the design assessment.

Remaining errors in fatigue life are not as significant as illustrated by Table 14. This is because substructure design is expected to be controlled at least partially by wind fatigue. Consequently, it seems reasonable to use this calibration process to propose a slightly conservative approach to wave fatigue as illustrated here. This will not have a huge repercussion on substructure weight

	Fatigue Life Ratios: True wave / Simplified waves 78-40			
	Position			
Location on Jacket	Leg Cans	Leg Attachments	Joint	Braces
Bay 1- Y joint	N/A	N/A	N/A	N/A
Bay 1- X Joint			N/A	N/A
Bay 2-Top K-Joint	1.25	1.24	1.20	1.30
Bay 2 - X joint			1.05	1.10
Bay 3-Top K-Joint	1.28	1.30	1.26	1.30
X Joint - Bay 3			1.20	0.85
Bay 4-Top K-Joint	1.62	1.59	0.94	1.32
X Joint - Bay 4			0.85	1.04
Top of Leg Can	1.11			
Bay 4-Bottom K-Joint			1.45	0.63
Top of Pile		1.58		
Pile	1.61			

$$\text{Life Factor} = \frac{\text{Fatigue Life from Omnidirectional: Metocean } Waves}{\text{Fatigue Life from Mean Fit Calibration: Simplfied waves}}$$

Figure 14. Fatigue Life factors for best fit approach

7. CONCLUSIONS

The following conclusions can be drawn from the discussion and analysis presented in the sections above:

- Establishing a simplified but representative correlation between the wind and wave conditions is a pre-requisite for any type of coupled analysis process between the wind turbine supplier and the substructure/foundation designer. It allows shorter run times to be achieved whilst still obtaining an accurate set of fatigue results to design the structure.
- Site specific correlation models based on simplified directional combinations as well as simplified sea state to wind speed relationships have been shown to be a viable and advantageous way to achieve the required correlation.
- However, mean fit relationships between Hs and Vw (50%-50%) have been shown to give significantly non-conservative fatigue lives, and should therefore not be used for design.
- Calibration of this correlation relationship is shown to be essential to obtain a simplified wave climate that yields fatigue lives that do not significantly under or overestimate those expected from the true wave climate at the site.
- An approach to this calibration using wave only spectral fatigue analysis has been illustrated. It has been shown how much improved calibration of fatigue damages may be obtained.
- In this calibration process, wave height relationships can be used to control overall fit, whilst wave period relationships can be used to control the balance of fatigue lives towards the top of the structure, relative to the bottom.
- Substructure design is expected to be controlled at least partially by wind fatigue and therefore the total combined fatigue lives are not likely to be as sensitive to wave fatigue. Consequently, it seems reasonable to use this calibration process to propose a slightly conservative approach to wave fatigue as it will not have a huge repercussion on substructure weight.
- The calibration exercise also compensates for the potential differences created by using a simplified directional model. The wave rose resulting from this simplified approach to wave definition may be slightly different from the site specific wave rose but fatigue lives will be similar.
- Care should be taken to ensure that sufficient accuracy is used in curve fitting the Hs vs V relationship, as erroneous results can easily be generated if the coefficients used for the fit are not accurate enough.

REFERENCES

[1]. Jason M. Jonkman and Marshall L. Buhl Jr. Loads Analysis of a Floating Offshore Wind Turbine Using Fully Coupled Simulation.National Renewable Energy Laboratory (NREL), Golden, Colorado, 80401-3393

[2]. IEC 61400 Wind Turbine - Part 3: Design Requirements for Offshore Wind Turbines, 2009

[3]. Det Norske Veritas & Germanischer Lloyd, DNVGL-ST-0126: Support Structures for Wind Turbine, April 2016 (Replaced DNV-OS-J101)

[4]. A. J. Adams and N. D. P. Barltrop. Dynamics of Fixed Marine Structures.

[5]. Det Norske Veritas & Germanischer Lloyd, DNVGL-RP-0005: Fatigue Design of Offshore Steel Structures, June 2014 (Replaced DNV-RP-C203)