INFLUENCE OF WAVE SPREADING IN SHORT-TERM SEA STATES ON THE FATIGUE OF OFFSHORE SUPPORT STRUCTURES AT THE EXAMPLE OF THE FINO1-RESEARCH PLATFORM

Prof. Peter Schaumann, Cord Böker
ForWind – Center for Wind Energy Research
Institute for Steel Construction, Leibniz University of Hannover,
Appelstr. 9a, 30167 Hannover, Germany
+49-511-762-2492; boeker@stahl.uni-hannover.de

Summary

The distribution of wave directions within a short-term sea state has a relevant influence on the fatigue loading of offshore structures. Measurement data collected at the FINO1 research platform will be used to demonstrate the effect. A better agreement between simulation and measurement can be achieved if wave spreading is taken into account in the simulation of the sea states. The effects of considering wave spreading both in the short-term as well as in the long-term will be studied at the example of a monopile and a tripod.

1 Introduction

Fatigue design of support structures for offshore wind energy converters (OWECS) requires the careful consideration of loads due to the surrounding waves in addition to the fatigue loads due to wind and the operation of the turbine.

It is common practice in the industry to simulate wave loads according to different sea states in the time domain by linear superposition of the particle kinematics of many linear waves having different amplitudes, periods, and phase angles. However, this approach assumes that the wave crests are infinitively long, so that all waves propagate only into one direction.

Obviously, this leads to inaccurate predictions of fatigue loads when compared to real-life measurements [4]. In this paper structural measurement data collected at the FINO1-research platform in the North Sea is used to investigate this inaccuracy and compare it to numerical simulation results.

2 FINO1 measurement data

At FINO1, a comprehensive measurement campaign is being carried out [1]. Besides measurements of environmental parameters like wind speeds, temperatures, and wave heights, structural data is being collected at eleven locations by means of strain gages. Figure 1a shows a schematical overview of the locations at which the structural data is measured. At each of these locations the axial force as well as the bending moments around the local y- and z-axes are measured and stored in a database that has been made up for this purpose.

In order to evaluate the impact of different directions of the sea states on the fatigue loading of structural details, as an example the axial force in the diagonal bracing has been investigated. This bracing is located at the south-western face of the submerged structure. Hence, it can be assumed that the axial force in the bracing becomes maximal for sea states whose directions coincide with the direction of the bracing, i.e. sea states from north-west (315° nautical) or from south-east (135°), respectively. The opposite case, sea states from 225° or 45°, perpendicular to the direction of the bracing, would lead to minimal axial loads in the bracings.

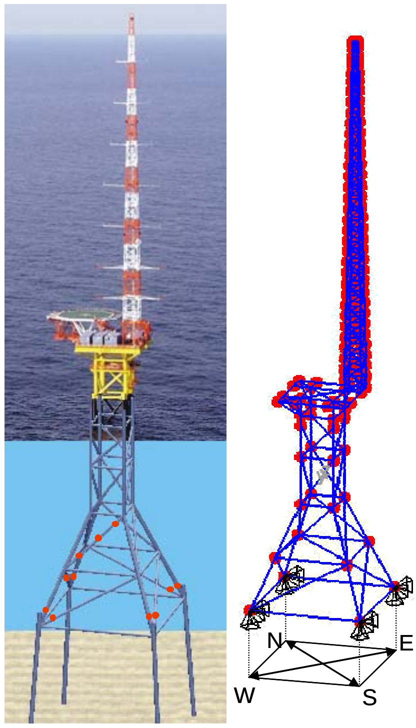


Figure 1: Research platform FINO 1 (photograph taken from [2]). a) Locations of strain gages. b) Numerical model and orientation with respect to nautical North

Two exemplary short term sea states have been chosen for comparative calculations: sea state 1 with H_s=1m and T_z=4s, and sea state 2 with H_s=3m and T_z=8s. Relevant periods in time with constrained sea state directions have been identified and the corresponding time series of the axial force have been picked from the database.

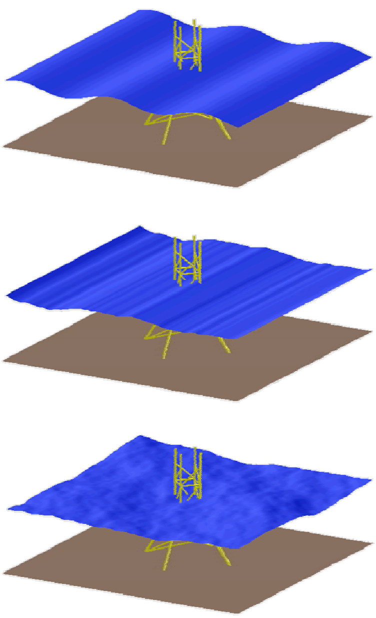
Afterwards, the damage equivalent loads (DEL) for these time series have been calculated, which allows a comparison to results of numerical simulations.

For these simulations a numerical model has been implemented, see Figure 1b. Wave loads have been generated as outlined in e.g. [3] and [5] using the Jonswap spectrum acc. to the approach mentioned above, i.e. the wave crests are modelled infinitively long, waves are propagating only into one direction. DELs have been calculated for the resulting time-series of the axial forces in the bracing. Figure 3 shows the comparison of measured and simulated data.

It can be clearly seen that the simulation results agree with the assumption regarding the sensitivity of the bracing to loading from different directions mentioned above, whereas the real-life measurements reveal a certain weakness of those assumptions. Even from the direction perpendicular to the bracing there is a significant amount of axial force in the bracing.

3 Numerical simulation with consideration of wave spreading

This can be explained with the so-called wave-spreading. This means the distribution of wave directions within a short-term sea state around the mean wave direction of the sea state. Acc. to [3], a stationary sea state with a duration of about 30 minutes can be regarded as a short-term sea state. Such a sea state can be best described by a superposition of many linear waves having different wave heights, periods, phase angles, and directions. Figure 2 illustrates the difference between a linear airy-wave and a short term sea state with wave spreading.



a)

b)

c)

Figure 2: Illustration of the difference between infinitively long wave crests and more realistically spread wave directions. a) Airy wave; b) Irregular, unidirectional sea state; c) Irregular sea state with wave spreading

Numerically, wave spreading can be considered by the application of a spreading function in the discretization of the wave energy spectrum, see e.g. [5]. The amplitudes A_{ij} for each partial wave can then be determined as follows [7]:

$$A_{ij} = \sqrt{2 \cdot S_i(\omega) \cdot D_j(\vartheta) \cdot \Delta\omega \cdot \Delta\vartheta} \qquad (1)$$

with
A_{ij} Amplitude of the partial wave
$S_i(\omega)$ Energy content for frequency ω
$D_j(\vartheta)$ Frequency of waves from direction ϑ
ω Wave frequency
ϑ Wave direction

In this paper the so-called $\cos^2$-spreading function has been used for comparative calculations:

$$D(\vartheta) = \frac{2}{\pi}\cos^2\vartheta; \quad -\frac{\pi}{2} \le \vartheta \le \frac{\pi}{2} \qquad (2)$$

with
D Spreading function
ϑ Wave direction

For a more detailed discussion of existing spreading functions and their properties refer to [7].

Figure 3 shows the results of numerical simulations with consideration of wave spreading.

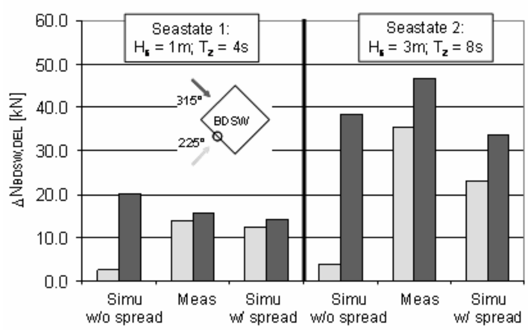


Figure 3: Comparison of measured and simulated damage equivalent axial forces in the bracing (detail D-BDSW) with consideration of short-term wave spreading

Especially for Seastate 1 with a relatively small significant wave height the results show a very good agreement. For the sea state with bigger wave heights there seem to be more influences to the axial force, like for example wind loads. This is subject to ongoing further investigations. However, it can be seen that a significant improvement of the agreement between measurement and simulation results could be achieved by considering wave spreading in the numerical analysis.

4 Influence over lifetime

The main drawback of considering short-term wave spreading in time-domain structural analyses are the significantly higher computation costs, because the number of directional classes multiplies the

number of components needed for the discretization of the wave energy spectrum. It is therefore important to know about the quantitative influence of wave spreading over the lifetime of the structures, especially in the pre-design phase of a project.
In this section the influence on typical structural details shall therefore be investigated at the example of a monopile and a tripod joint.
To study the long-term effects, a simplified scatter-diagram acc. to [8] has been used. This scatter diagram represents a condensed scatter diagram for North Sea conditions and is given in the following table:

i	H_s	T_z	Freq.
1	0.50	2.5	9.1
2	0.80	3.5	93.1
3	1.17	4.5	253.4
4	1.60	5.5	355.2
5	2.28	6.5	208.2
6	3.33	7.5	62.8
7	4.44	8.5	14.2
8	5.53	9.5	3.3
9	6.22	10.5	0.6
10	5.07	11.5	0.1

Table 1: Scatter diagram acc. to [8] for North Sea conditions

For the long-term distribution of sea state directions $\cos^2$-spreading has been assumed, too. Obviously, this is a simplification, but it allows for a general investigation of the impact of short-term wave spreading when combined with long-term effects.

4.1 Monopile

The monopile is a good example to study the effects of wave spreading, because stresses somewhere around the circumference of the pile only depend on the bending moment. Hence, the calculation and superposition of different load conditions is fairly simple.
As mentioned above, the distribution of wave or sea state directions can generally be considered in the long-term (distribution of sea state directions, long-term spreading) as well as in the short-term (distribution of partial wave directions within a sea state, short-term spreading). Hence, the following four cases can be studied, with increasing demand of calculation time:

	Long-term spreading	Short-term spreading
1	No	No
2	Yes	No
3	No	Yes
4	Yes	Yes

Table 2: Four different cases for consideration of wave spreading in numerical analyses

Here, the damages resulting from numerical simulations for all four cases will be considered for the monopile. Case 1 will be taken as reference so that the benefits of taking spreading into account can be easily seen. The monopile used for the simulations has a first natural frequency of 0.297 Hz and a diameter in the submerged part of 7m in 30m water depth. These dimensions are somewhat academic as no appropriate driving gear is available in the market to date, but nevertheless this configuration is a mechanically feasible solution for an actual 5MW machine in moderately deep water.
Figure 4 shows the relative damages resulting from the four cases over a half-circumference of the pile at mudline. The mean wave direction in all simulations has been 0°. A $\cos^2$ spreading function has been applied both in the long-term and in the short-term. As expected, the reference case 1 without short-term spreading and unidirectional simulation of the sea states yields the highest damage. As shown above at the example of the FINO1 platform, this result is conservative. Considering long-term spreading already reduces damages to an amount of about 62%, cf. also [5]. As can be seen, the amount of damage that has been reduced at the point of the biggest damages for case 1 has been disseminated around the circumference of the pile. The area under the curves remains the same. This can be interpreted such that the overall wave energy causing the damages remains the same independently of the spreading function applied.
Case 3, i.e. unidirectional sea states with short-term spreading applied, yields a similar result. The highest damages are reduced to about 67%. Also here, it can be seen that damages due to waves in the mean wave direction has been reduced and spreaded around the structure.
Combining both long-term and short-term effects in the analysis gives the smoothest curve in the visualization of Figure 4. The maximum damage has been reduced even further to some 46% of the maximum damage, while the damages at the border of the diagram have been increased.

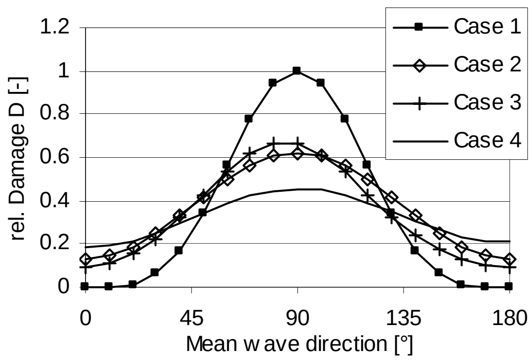


Figure 4: Relative damages around the half-circumference of a monopile at mudline due to wave loading acc. to Scatter-Diagram from Table 1 for mean wave direction 0°.

It is important to note that the increase of fatigue loading at points that are not loaded by single waves in the mean wave direction occurs. This has especially an impact on more complex structures where stresses also depend on restraints in hyperstatic systems. This is the case e.g. for the Tripod, which will therefore be scrutinized more thoroughly in the next section.

4.2 Tripod

The monopile example showed that the consideration of wave spreading in the long or in the short-term will lead to a significant reduction of fatigue loads and resulting damages. In this section a typical structural detail of a more complex support structure type shall be investigated. As an example the upper joint of a tripod has been chosen for this study. The tripod model used has been published in [6]. Figure 5 shows the dimensions of the tripod.

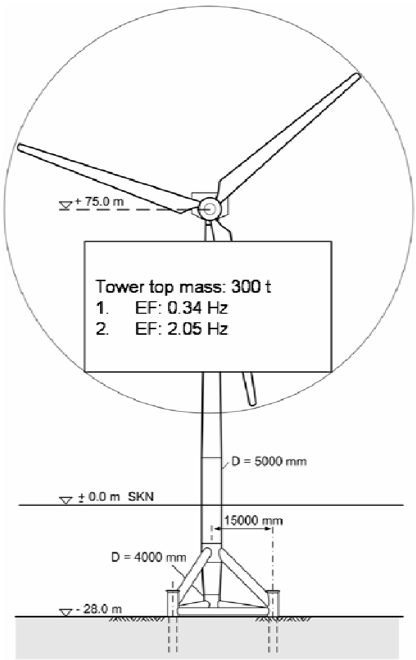


Figure 5: Tripod dimensions used for the comparative calculations investigated in this paper.

Obviously, for this system the structural strain in the braces depends on the loading direction. Hence, the direction in which the strain becomes maximal for the detail of interest has to be determined. In order to minimize the calculation time needed for this task a transfer function that correlates the wave direction to the structural strains of interest utilizing an analysis with linear single waves can be applied.
In Figure 7 the maximal nominal stresses at the brace-crown and brace-saddle of the brace pointing to nautical East due to loading of a single wave from different directions are shown. For a definition of crown and saddle location see Figure 6.

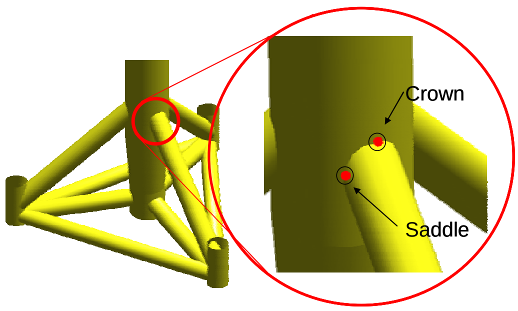


Figure 6: Definition of brace crown and brace saddle

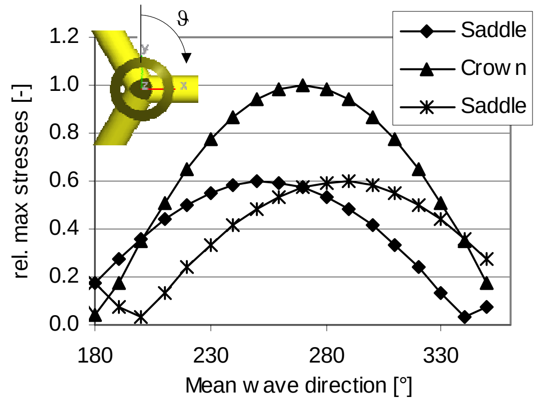


Figure 7: Related maximal nominal stresses at brace crown and brace saddle location.

As expected, the stresses at the brace crown have their maximum for waves from 270 deg, i.e. in the direction of the brace. This is because the stresses at the brace crown mainly depend on the axial force in the brace and the in-plane bending moment, which are in phase, cf. Figure 8. Therefore, it can be expected that the benefits and the behavior with regard to wave spreading for this detail compare to the monopile investigated above.

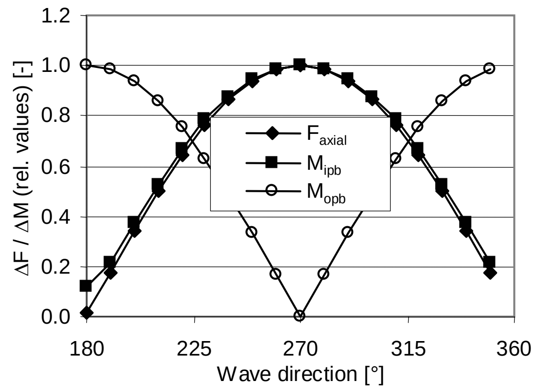


Figure 8: Related axial force F_{axial} and bending moments M_{ipb}, M_{opb} in the brace over varying wave directions.

The stresses at the brace saddles depend on the axial force and the out-of plane bending moment. Since these are not in phase, it depends on the geometrical setup of the actual structure and the ratio between axial force and out-of-plane moment to what extent each of these components influences the stresses at the saddle. Typically, the wave direction due to which the stresses at the saddle become maximal will not be the same as for the crown. Ideally, this makes the analysis of many different mean wave directions necessary to cover the worst case for every location around the weld of the joint.
In the pre-design phase unidirectional calculations will usually be performed in order to save calculation time. The mean wave direction will be pragmatically chosen such that governing stresses for most of the required details will be gained. In the example the

simulations would be run with a mean wave direction of 270 deg, which will produce the highest stresses in the brace crown. However, the error in stresses for the saddle will be about 4% in the example above. Assuming a constant slope of the SN-curve of m=4, which is fair enough as a first guess, this equals to an error of about 17% in damages. For other structural configurations this could even increase depending on the ratio of axial force and out-of-plane moment as described above. Therefore, it is important to know how much savings in damage can be offered by the consideration of spreading, e.g. during the detailed design of the structures.
Figure 9 shows the fatigue damage at brace crown and brace saddle yielding from analyses acc. to Table 2. As can be seen, significant savings in fatigue damage of up to 70% can be achieved by considering wave spreading in the analysis. It has to be noted, though, that the absolute amount of damage that can be mitigated depends on the structural configuration.

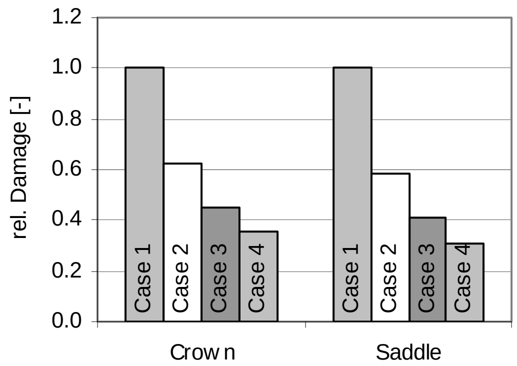


Figure 9: Related damages at brace crown and brace saddle due to the four cases from Table 2

5 Conclusions

In this paper the structural measurement data collected at the FINO 1 research platform has been used to evaluate the sensitivity of structural details to the direction of wave loading. It was shown that the approach of simulating sea states with infinitively long wave crests, which is commonly used in the industry, leads to very conservative results. Considering wave spreading in short-term sea states can reduce the resulting fatigue loads significantly. This has been demonstrated at two examples, a monopile and a tripod. However, consideration of wave spreading increases calculation time significantly and is therefore not recommended for pre-design calculations. Therefore, it has been shown how wave spreading can help account for inaccuracies that are accepted during pre-design for the benefit of efficiency in the design.

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6 References

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