Comparison of different approaches to load calculation for the OWEC Quattropod jacket support structure

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Abstract. Accurate load simulations are necessary in order to design cost-efficient support structures for offshore wind turbines. Due to software limitations and confidentiality issues, support structures are often designed with sequential analyses, where simplified wind turbine and support structure models replace more detailed models. The differences with an integrated analysis are studied here for a commercial OWEC Quattropod. Integrated analysis seems to generally predict less damage than sequential analysis, decreasing by 30-70 percent in two power production cases with small waves.

Additionally it was found that using a different realization of the wave forces for the retrieval run in sequential analysis leads to an increase of predicted damage, which can be explained as the effect of applying two independent wave force series at the same time.

The midsection of the detailed support structure model used shell elements. Additional analyses for a model with an equivalent beam model of the midsection showed only small differences, mostly overpredicting damage by a few percent. Such models can therefore be used for relatively accurate analysis, if carefully calibrated.

1. Introduction

The design of support structures for offshore wind turbines is based on accurate load calculations with numerical computer models. Conformity of the design to the required serviceability, ultimate and fatigue limits is thereby assessed. Different modeling approaches, computer codes, and the way in which calculations are performed can significantly influence the results. This can potentially lead to overconservative designs, and a better understanding of the issues involved might offer the possibility of further optimizing support structures and reducing their costs.

In this study we considered a commercial OWEC Quattropod® designed by OWEC Tower AS for a water depth of 26.1m in the Thornton Bank project. One of the five different structures designed for this site was selected. The load calculations and certification in this commercial project were performed in cooperation between the support structure designer OWEC Tower AS, the wind turbine manufacturer REpower Systems AG and the engineering consultancy TDA. Basis for most load calculations was a sequential analysis [9] that allows for cooperation between all parties involved without sharing detailed computer models.

Sequential analysis as pioneered by REpower consists of three distinct steps. In a first step, only the support structure model is used without a tower and wind turbine model included. Simulations were performed with ANSYS ASAS(NL) (Version 13, ANSYS Inc., Canonsburg) and result in generalized mass, damping and stiffness matrices together with a generalized load time series that essentially consists of the integrated wave loading experienced by the support structure. In a second step a wind turbine simulation is performed in a variant of FLEX5 (Stig Øye, DTU) with this reduced model for the support structure. Displacement time series at an interface node are output that reflect the response to combined wave and wind loading. In the final step these time series are applied to the detailed support structure model, including exactly the same wave loading used for the first step.

The sequential analysis replaces the earlier *semi-integrated* approach [10] in which an equivalent beam model was used for the support structure in the second step. Both approaches have in common that the wind turbine simulations are performed with a simplified model for the support structure. In contrast to this, a *fully-coupled* or *integrated* simulation will simulate the wind turbine with a detailed model of the support structure. A number of studies have hypothesized that for such a complex and tightly coupled system fully-coupled simulations are needed to obtain accurate results, especially with regard to local vibrations of the support structure [12, 2].

Even if integrated analyses are performed, the question remains how accurate and realistic the results are, compared to the actual behavior of the system. The Offshore Code Comparison Collaboration (OC3) project headed by Fraunhofer IWES (Bremerhaven) and the National Renewable Energy Laboratory (Boulder, Colorado) has performed systematic studies of differences in load calculations obtained by different simulation codes. During its successor, the OC4 project under Task 30 of IEA Wind, a prototypical support structure of the jacket type was studied [7]. Although results generally agree within 10 percent for displacements and forces, damage equivalent loads differ to a larger extent, with up to 50 percent or more in some cases.

The goal of the present study was to study differences in load simulations for a commercial OWEC Quattropod® design, which contains many more features and details than the OC4 jacket. Three main questions were addressed:

(i) What are the differences in load calculations between different analysis codes?
(ii) What differences can be seen between fully-coupled/integrated and sequential load calculations?
(iii) What is the influence of various changes in model detail?

2. Methods

Currently, not many software packages allow for an integrated analysis of a complete offshore wind turbine on a jacket structure. We have performed most analyses with Fedem Windpower (Fedem Technology AS, Trondheim), which is a flexible multibody solver that has been extended to provide both aerodynamic and wave loads. Fedem Windpower has been verified in the OC3/OC4 project and we used a pre-release version of the software. Alternatively, Bladed (Version 4.2, GL Garrad Hassan, Bristol) was used. Both simulation codes were at present not able to run all cases of this study with the OWEC Quattropod® and all its features included.

Although integrated wind turbine analyses can be performed with Fedem Windpower, it currently does not provide functionality for implementing non-diagonal elements of generalized stiffness and damping matrices necessary for the second step of the sequential analysis. The wind turbine simulations with a simplified support structure model were therefore performed by Bladed (Fig. 1).

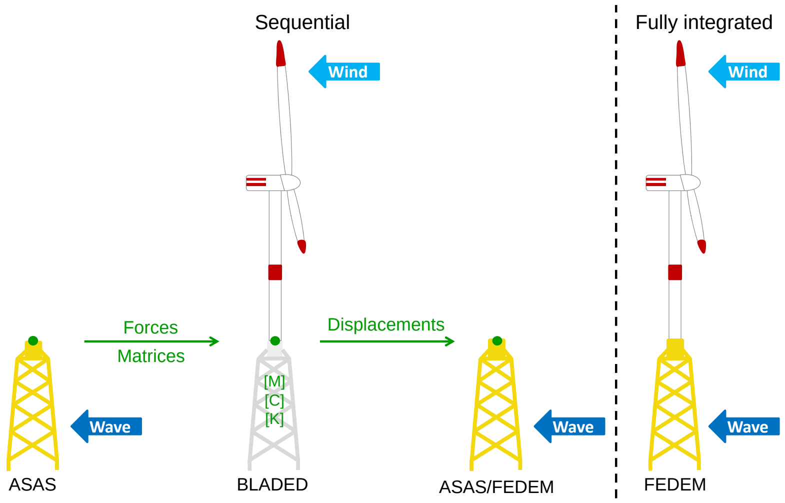

Figure 1. Sequential and integrated analysis as performed in this study.

The current version of Bladed has limitations with respect to the number of nodes and elements available. Although the support structure could be fully implemented up to mudline, it was not possible to obtain simulation results when the soil piles were included. The Bladed model of the complete wind turbine was therefore rigidly connected to the ground at mudline level. It is also not possible to include freedom releases and rigid element offsets in Bladed, and Bladed does not offer shell elements for modeling the transition piece and deck. Mass, stiffness and damping matrices for the sequential analysis were included in Bladed as a "soil model", but it was not possible to use non-diagonal elements in the mass matrix. The latter is no practical limitation since these, corresponding to the effect of geometric nonlinearities, were a factor of 1000 smaller than the diagonal elements. Finally, a short rigid element at the top of the transition piece had to be modeled with flexible material.

Retrieval runs (step 3 of the sequential analysis, Fig. 1) were performed with both Fedem Windpower and ASAS models of the support structure, since Bladed does not easily allow for structural analyses without a wind turbine, and does also not provide many of the more detailed features needed for accurately modeling the support structure.

2.1. Simulation models

The support structure models were based on the final ASAS model of the OWEC Quattropod® used in the certification analysis. This is a finite-element model with more than 900 nodes and elements, including both beam and 4–node shell elements, as well as (linear) springs and dashpot elements for the soil piles (Fig. 2*a*). The model has been exactly replicated in Fedem Windpower. This model is called FEDEM1 in the following (Fig. 2*b*). For the integrated simulations the NREL 5MW reference wind turbine [6] was implemented on top of the jacket, with an additional point mass of 100t to more closely match the REpower 6M turbine. Also the damping was adjusted (see below). This model was called FEDEM3 (not shown). The models were run for 600s with output time steps of 0.02s. The first 100s of results were discarded in order to remove possible transients. A full overview over all FEDEM models used in this study is given in Table 1.

2.2. Reduced midsection

Since Bladed does not supply shell elements, the middle section with the transition piece was represented by an equivalent beam model in Bladed (Fig. 2*c*). This reduced midsection was obtained by manually adjusting element properties in order to match mass and stiffness. The

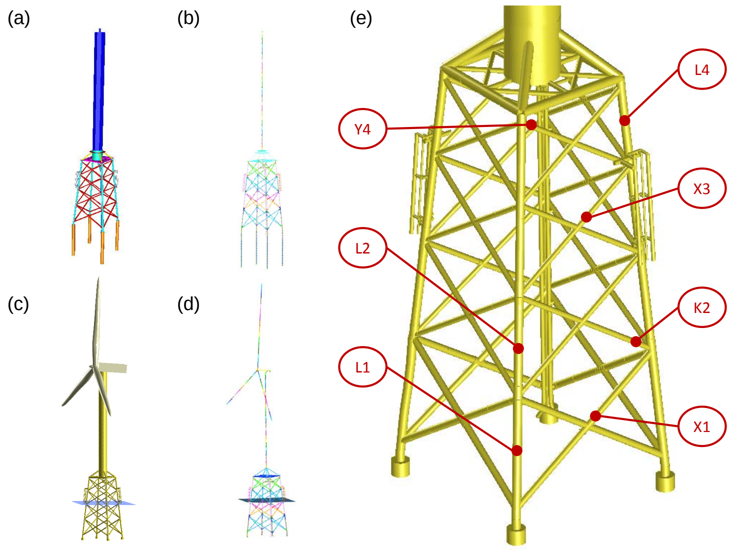

Figure 2. Simulation models in this study.
(a) ANSYS ASAS,
(b) FEDEM1,
(c) BLADED1,
(d) FEDEM4,
(e) Detail of the model with reduced midsection, including output locations.
FEDEM3 is a combination of the FEDEM4 turbine and the FEDEM1 jacket.
BLADED2 is BLADED1 with the jacket removed and represented by generalized matrices.
L: leg; X, K, Y: type of joint. Number denotes bay, counting from bottom.

Table 1. Overview of FEDEM simulation models.

Identification	Description
FEDEM1	configuration identical to ANSYS ASAS model
FEDEM2	as FEDEM1, with reduced midsection
FEDEM3	as FEDEM1, with modeled NREL 5MW turbine
FEDEM4	as FEDEM3, with reduced midsection

latter was assessed by comparing the first five eigenfrequencies (Fig. 3). The same integrated model was exactly reproduced in Fedem Windpower and called FEDEM4 (Fig. 2d). The midsection was also replaced by this reduced midsection for the FEDEM1 model, which is then called FEDEM2.

2.3. Output stations
Responses were recorded at all nodes and members of the support structure, of which only a few are discussed here (Fig. 2e). These output stations consist of nodes on the legs and braces, and are named either as leg (L) nodes or according to the closest joint (X-, K-, and Y-type). The jacket has four bays, which are numbered starting at the bottom, such that, e.g., K2 denotes the K-joint on the second-lowest bay.

2.4. Damping
The ASAS model of the OWEC Quattropod® was implemented with Rayleigh damping, i.e., element damping matrices are linear combinations $C = \alpha M + \beta K$ of element mass (M) and stiffness (K) matrices. This was exactly reproduced in Fedem Windpower. Bladed uses a modal basis for simulations, and a damping ratio ζ needs to be specified for each such mode.

If all elements were using the same Rayleigh damping coefficients α and β, this would be given by $\zeta(\omega) = \frac{1}{2}\left(\frac{\alpha}{\omega} + \beta\omega\right)$ [3]. In extension of this, the Rayleigh damping coefficients were here taken as averages $\alpha = \sum_i \alpha_i m_i / \sum_i m_i$, $\beta = \sum_i \beta_i m_i / \sum_i m_i$ of the coefficients α_i, β_i of all elements, weighted by the magnitude m_i of the i-th component of the corresponding eigenvector (modeshape). Results (see below) seem to indicate good agreement. For the wind turbine, the damping was slightly adjusted and differs from the damping specified by NREL (in order to mask results for confidentiality reasons).

2.5. Damage factors

Responses were assessed by visual inspection of time series, second order statistics, probability density functions and spectra. An approximate, relative assessment of damage was obtained directly from the displacement time series. Rainflow counting was performed and damage was integrated using Palmgren-Miner's rule with a load-N curve (displacement versus allowable cycles to failure), similar to the approach in [4]. The ultimate displacement before failure was taken to be 1.0m and an inverse slope $m = 3$ was used. The results cannot be compared for different nodes because of differing geometry, but for different loadcases (as long as they are based on timeseries of the same length). For most plots (see below) the results were additionally normalized to a reference damage value such that relative changes in damage are reported.

3. Results

In the following the different models are compared, with respect to four questions:

(i) Can the support structure be analyzed in both ASAS and FEDEM with similar results?
(ii) Can the wind turbine be analyzed in both FEDEM and Bladed with similar results?
(iii) Are there differences in support structure behavior for the reduced midsection?
(iv) Are there differences between fully-coupled and sequential results?

Three classes of models were considered and directly compared:

- ASAS and FEDEM1/FEDEM2 are models of only the support structure, whereas
- BLADED1 and FEDEM3/FEDEM4 are models of a complete wind turbine.
- FEDEM4 and BLADED1 are both clamped at mudline.

Comparisons are typically only within each class. For fully-coupled simulations FEDEM3 is used, for step 2 in the sequential analysis BLADED2 is used, and FEDEM1 and ASAS are used for the retrieval runs.

Two main environmental conditions were used for the power production loadcases that are relevant for fatigue lifetime estimation:

(A) irregular waves with $H_s = 1.0\,\mathrm{m}$, $T_p = 4.95\,\mathrm{s}$ and $\gamma = 1.06$ from a JONSWAP spectrum, and turbulent wind at $U = 8\,\mathrm{m/s}$ from a von Karman spectrum with turbulence intensity $I = 0.153$;
(B) irregular waves with $H_s = 2.59\,\mathrm{m}$, $T_p = 6.99\,\mathrm{s}$ and $\gamma = 2.13$; turbulent wind at $U = 20\,\mathrm{m/s}$ with $I = 0.121$.

Many additional load cases were used for testing specific aspects of the models (see below).

3.1. Mass and center of gravity

The total mass for the ASAS model is 1337t, which is closely matched by the other models (within 1.5 percent). The center of gravity lies within 1.6 percent for the vertical axis and less than 6.0 percent horizontally. The only exception are the models with reduced midsection which exhibit a horizontal deviation of a few cm (amounting to 20 percent relative error).

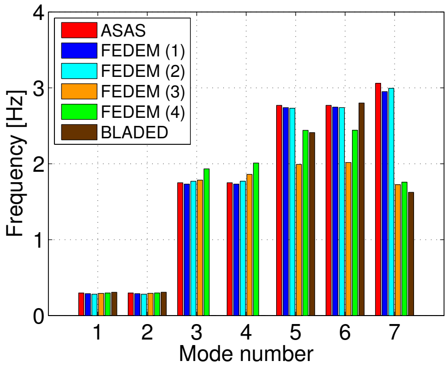

Figure 3. Comparison of first seven eigenfrequencies.

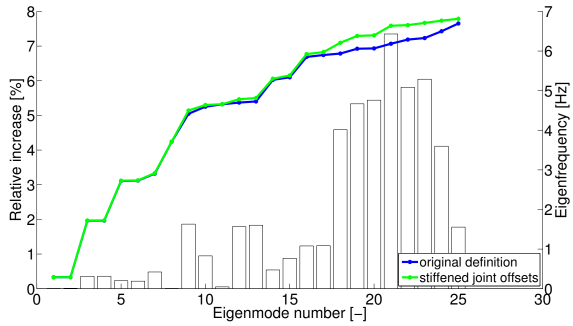

Figure 4. Eigenfrequencies and relative changes for FEDEM model with and without local element offsets.

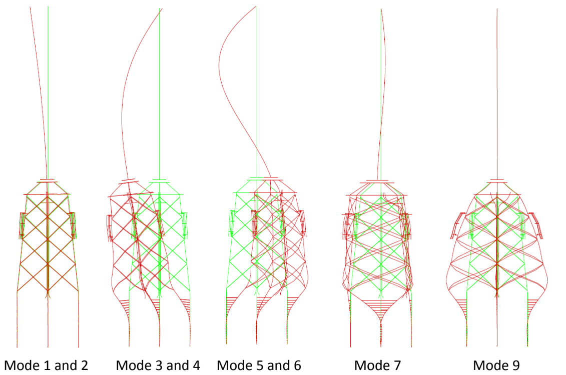

Figure 5. The first nine modeshapes of the ASAS model.

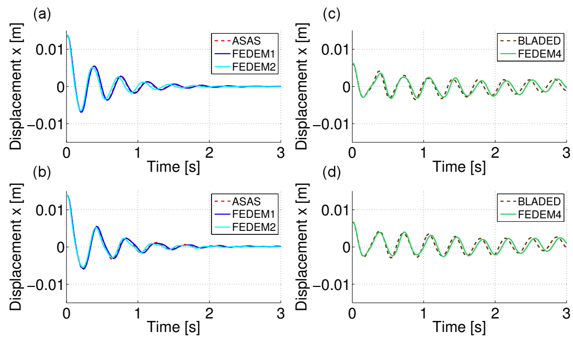

Figure 6. Decay test with a 1MN force applied at tower bottom and released at $t = 0\,\mathrm{s}$. Horizontal displacements at L4. (a, c): in air; (b, d): in still water.

3.2. Eigenfrequencies

The first seven eigenmodes were compared (Fig. 3) and showed relatively good agreement between ASAS and FEDEM1/FEDEM2, or between FEDEM4 and BLADED1. Differences between detailed models and models with reduced midsection are only evident for the complete wind turbine. It should be noted that such a comparison is at best approximate, since there exist various ways of defining dynamic modes for rotating, flexible multibody systems. For example, in Bladed the first tower modes are obtained by considering unit loads in all six degrees of freedom (with the rotor-nacelle assembly represented by a point mass and inertia), and then further modes normal to these [1]. Comparing the modeshapes visually allows to identify similar modes (Fig. 5), but cannot resolve such differences.

3.3. Static load cases

Two static load cases, with either 1MN or 1MNm applied at the tower bottom, showed good agreement between all models (in each class). The much stiffer clamped models exhibited only 50 to 25 percent of the displacements.

3.4. Free decay behavior

Free decay behavior of the support structure models was assessed by ramping up a 1MN horizontal load and releasing it at $t = 0\,\mathrm{s}$. ASAS and FEDEM1 showed excellent agreement,

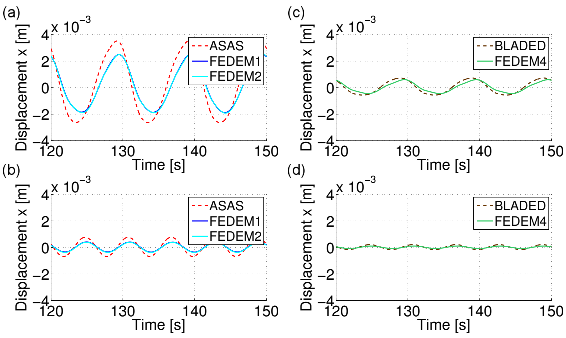

Figure 7. Response to regular wave loading at output location L2. (a, c): $H = 6$ m, $T = 10$ s; (b, d): $H = 2$ m, $T = 6$ s.

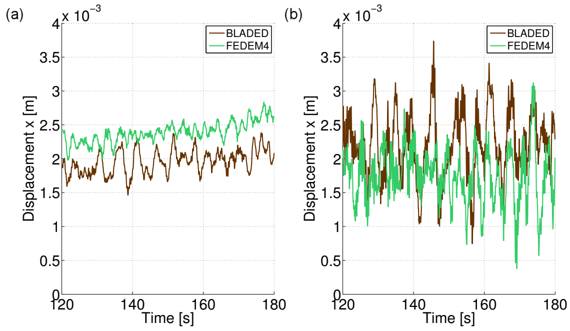

Figure 8. Integrated models BLADED1 and FEDEM4. Example response time series at output location X3. (a): Environmental conditions A. (b): Environmental conditions B.

both in air (Fig. 6a) and still water (Fig. 6b). Model FEDEM2 with reduced midsection showed a slightly shorter period due to a somewhat smaller first eigenfrequency, but with similar amplitude. The comparison between FEDEM4 and BLADED1 showed similar agreement (Fig. 6c, d). Interestingly, at first the results for ASAS did not match the FEDEM results, but after consulting with TDA it was confirmed that one needs to specify a very small wave in ASAS in order to obtain the contribution from the added mass.

3.5. Behavior under regular and irregular waves

The response was studied both for regular and irregular waves based on linear wave theory. Surprisingly, results for regular waves with $H = 6$ m, $T = 10$ s (Fig. 7a) and with $H = 2$ m, $T = 6$ s (Fig. 7b) showed that the response in ASAS is significantly higher (around 100 percent increase for the 2m wave, and around 40 percent for the 6m wave) than for the FEDEM models. Essentially the same difference was seen for irregular waves. In order to understand this phenomenon better, regular waves with $H = 2$ m, $T = 30$ s were additionally studied (not shown). Such a slow wave far away from resonant frequencies leads to a quasi-static response, which is essentially due to wave forces (inertial effects are thereby avoided). Still, we found differences in response amplitude of 20-25 percent. This suggests that wave loads are generally higher in ASAS. Although the wave loads in FEDEM have been verified in the OC3/OC4 project, the details in which these are resolved and integrated might still cause such a difference.

The reduced midsection in FEDEM2 did not influence the response to the same extent, with a maximum difference of up to 20 percent for the lower bays in the 2m wave. The comparison between BLADED1 and FEDEM4 also showed a slight underestimation of wave loads of about 15-20 percent in FEDEM.

These differences were systematically larger for the smaller waves, which suggests that they might be mainly caused by the calculation of the wave forces in the splashzone. Additionally, the influence of marine growth was assessed. This generally led to larger displacement amplitude (due to higher wave loads), and showing similar differences consistent with the above.

3.6. Influence of local joint modeling

The ASAS model contains element offsets at joints to model local joint behavior. These were reproduced (manually, with rigid beams) in the FEDEM models. Since this is of general interest, we studied the behavior of the model without these offsets. For the lower eigenmodes the

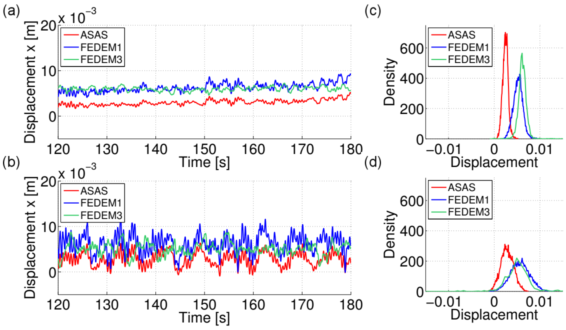

Figure 9. Results for sequential (ASAS, FEDEM1) and integrated analyses (FEDEM3) according to Fig. 1. (a, b): Example time series for X3 joint. (c, d): Probability density functions of these responses. (a, c): Environmental conditions A. (b, d): Environmental conditions B.

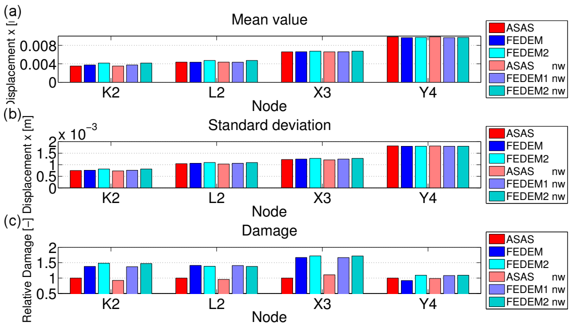

Figure 10. Comparison of responses in sequential analysis between models and for waves / no-waves (nw) in the retrieval run. Environmental conditions similar to A.

differences were minimal (below 0.5 percent), but the eigenfrequencies were increasing by 4-7 percent for higher modes that correspond to local vibrations (Fig. 4).

Running a typical power production case, no systematic, clear trend of changes was discernible. In total, however, both the standard deviations and the damage factors were higher with stiffened joint offsets, up to 20 percent, or in some cases (K2) even up to 50 percent.

3.7. Sequential analysis with a reduced model

This is the main case of interest for this study. Since the wind turbine was simulated with BLADED2 in step 2 of the sequential analysis, and with FEDEM3 in the integrated analysis, we first compared integrated analysis between BLADED1 and FEDEM4 (Fig. 8). The results showed good agreement, although a few differences (e.g., in mean displacements) existed (not shown).

The influence of correctly implementing the wave loads was separately studied. Removing the wave forces in the retrieval run led to small differences (Fig. 10); for these fatigue cases with relatively small wave height the response of the support structure seems to be dominated mostly by wind loads. In general, a small decrease in damage (up to 5 percent) seems to result.

Differences for the retrieval runs between ASAS and FEDEM were much more pronounced, with up to 60 percent higher damage in FEDEM1, and a few percent more for the reduced midsection model. Again, this could be caused by a different integration of wave forces in FEDEM. Additionally, the retrieval run is performed with displacements that ultimately were obtained from wave forces by ASAS. These changes can therefore also reflect changes due to using a different realization of irregular waves, which in effect amounts to using wave forces twice. Not using the wave forces from ASAS results in a negative response, using the wave forces from FEDEM results in a second positive response. Since these responses are completely independent of each other, on the average there will be a net effect that will be larger than for using wave forces once. In contrast, output Y4 is not directly affected by waves and therefore shows little differences.

The same comparison was used for assessing the differences between sequential and integrated analysis for both environmental conditions A and B (Fig. 11). Two additional nodes L1 and X1 were included in this comparison. For environmental condition B some convergence problems

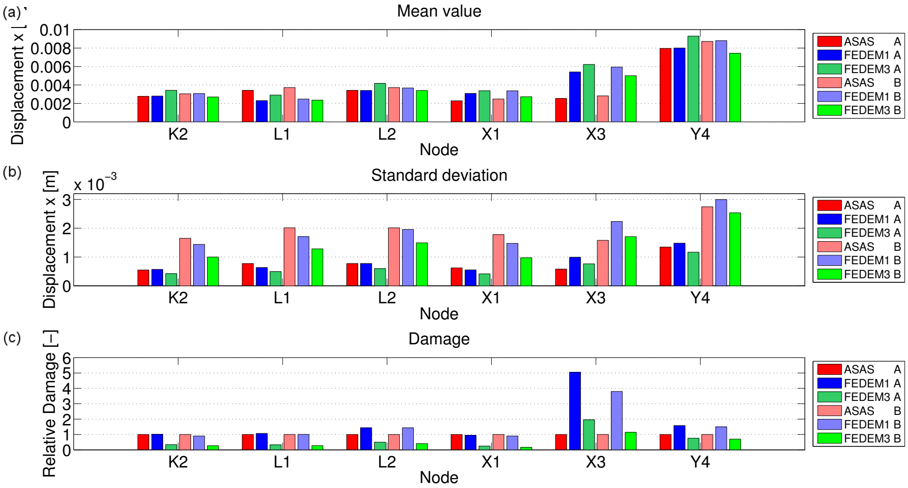

Figure 11. Comparison of sequential and integrated analysis.

were encountered, such that these results are only based on 200s of simulation time. The main result is that damages in the integrated analysis were significantly lower than in the sequential analysis (reduced by 30-70 percent), with the notable exception of the X3 brace that showed an increase of 100 percent for the small waves of environment A. As before, sequential retrieval runs with FEDEM1 suffered slightly from mismatches in wave forces. Again, the X3 brace, located relatively close to the splashzone, is an exception and exhibits the most damage.

4. Discussion

Accurate and reliable load calculations are important for the design, the optimization and the certification of offshore wind turbines. Current projects are complicated by (a) the commercial unavailability of wind turbine analysis software with all features required for integrated analyses with complex support structures, and (b) the necessity felt by the industry of keeping model details confidential. Sequential analysis has been introduced as a potential solution, but soon its limitations were detected.

4.1. Sequential analysis with a complete model

In general there seems to be some misunderstanding in literature about the conceptual foundation on which sequential analysis is based. *Substructuring methods* have been around almost since the beginning of finite element analysis [8]. When sequential analysis is performed with an identical model of the support structure and the same environmental conditions, using displacements at an interface node, results will be *identical* to an integrated analysis. This was confirmed by simulations (not shown). Differences in results will occur only because of (a) different software used for the analyses, (b) different environmental conditions (e.g., through different random number generators), and (c) because of different detail in the support structure model used.

4.2. Integrated versus sequential analysis

In this study the integrated analysis resulted in significantly reduced damage factors (with the notable exception of an X-brace in the top part of the jacket). Although the comparison is not perfect, since different software were used for the sequential and the integrated analysis, this indeed suggests the need for integrated analyses in the design of support structures for offshore wind turbines.

It is hoped that the limitations in current wind turbine analysis software will be addressed and fixed in the near future, such that integrated analyses of complex support structures become feasible and efficient soon.

4.3. Reduced midsection

The reduced midsection models showed slight differences in eigenfrequencies, so responses / excitations will generally differ to a certain extent. However, almost no influence on the response due to (regular and irregular) wave loads was detected. Also in the sequential analysis, only slight differences were observed (Fig. 10), generally overestimating the damage by a few percent.

4.4. Different analysis codes

Both FEDEM and ASAS showed larger differences in response to wave loads than expected. This should be further studied.

In general we can conclude that using different waves in the retrieval step of the sequential analysis did have a significant influence on the damage for these cases with relatively small waves, but will generally be conservative and limited to a factor of two at most. The situation should be studied more closely for larger waves and, for example, assessing the ultimate limit state behavior.

Acknowledgments

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