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FATIGUE ANALYSIS ON INNOVATIVE 10 MW OFFSHORE JACKET STRUCTURE USING INTEGRATED DESIGN APPROACH

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ABSTRACT

The fatigue limit state (FLS) of fixed offshore wind turbine structures is critical and difficult to handle. As it is the most common design driving criteria for offshore structures, the simulation and calculation of this phenomenon must be as accurate as possible. Research is needed to improve the current design. There are mainly two design approaches available: Integrated design approach (IDA) and Sequential design approach (SDA). The IDA, described in this paper, considers the coupled structural analysis of a whole wind turbine system exposed to wind- and wave-induced loads in an aero-hydro-elastic solver. The results given by solver are loads series, which are afterwards used for obtaining the stress series with stress concentration factors (SCF) included. The stresses are processed in terms of rainflow counting and finally, fatigue damage of a critical K-joint is obtained externally, to avoid the use of damage equivalent loads (DEL) as by default in the solver, but to calculate it by means of the Efthymiou principle. The whole procedure with methods is explained in this paper.

NOMENCLATURE

OWT = Offshore Wind Turbine
IDA = Integrated Design Approach
SDA = Sequential Design Approach
FLS = Fatigue Limit State
SCF = Stress Concentration Factor

1. INTRODUCTION

Steel jackets are support structures employed for offshore wind turbines (OWTs) in deeper waters, due to the higher stiffness at the footprint and the smaller surface facing the wave loads compared to the monopiles which are dominating the offshore wind turbines market. Furthermore, when talking about the new OWT installations in the EU in year 2016, jackets have a significant increase to 12% of all OWTs installed, compared to the year 2015 (Fig.1).

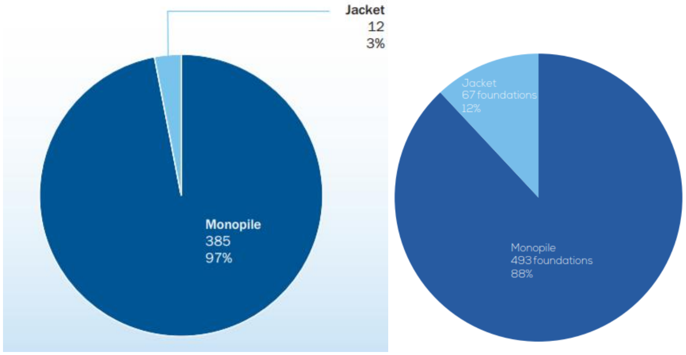
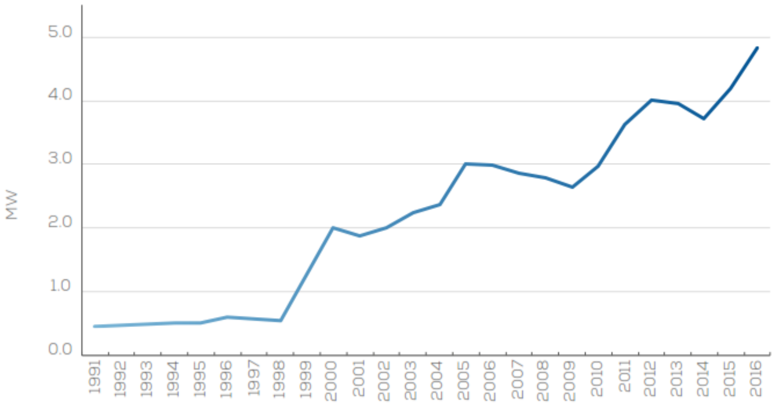


Figure 1. Foundation types installed in 2015 (left) and 2016 (right) annual market

The general trend in the offshore wind turbine industry nowadays is increase of the maximum capacity, as shown in the Fig. 2. Recently, turbines with output of 10 MW have been installed, and in the future, sizes are expected to grow up to 20MW, if proven economically and technically feasible [6, 7].

The size increase brings up the problem of larger generators, higher hub heights and larger structures and foundations, which leads to higher dynamic complexity of offshore wind turbines. As OWTs are exposed to cyclic aerodynamic, hydrodynamic and mechanical loading, they are especially prone to fatigue damage. This is a main design driving criteria, so constant research and improvements are needed in the approaches for fatigue analysis. Two mainly used approaches in the industrial design are IDA and SDA with superelements.



Source: WindEurope

Figure 2. Average offshore wind turbine rated capacity in MW

The IDA considers the coupled structural analysis of wind and wave loads in one software only, while the SDA runs a separate aero-elastic analysis and takes only the interface loads from it for the further analysis in other offshore code. Both approaches have their own advantages, and are used depending on the case requirements and conditions. The main advantage of the SDA is that it supports the use of superelements, which allows the foundation designer to share their design for aero-elastic analysis without needing to share the detailed jacket design with the wind turbine manufacturer, as well as the fact that is can include some complex support structure elements (like shell elements) into the dynamic response of the structure.

However, the IDA has many advantages over the SDA. It includes the full coupling between wind and wave loads and the structure, while for the SDA hydro-elastic coupling is omitted, as the wave loads are given only as a simulation input. Next, by separating the simulations of wind and wave loads at SDA, the duplicated simulations must be conducted, which is not the case with IDA. Finally, the overall system optimisation is easier in fully integrated model, and that is the reason why calculation of the fatigue damage is here chosen to be conducted by means of IDA [1,4,5].

2. METHODOLOGY

The integrated FLS design is here conducted using the offshore code SESAM GeniE for structure modelling, and software Bladed for wind and wave loads computation and structural analysis. The workflow of the integrated design is visualized in the Figure 1 and described in following steps:

- Creating the jacket structure FE model in SESAM GeniE and converting it into the Bladed-readable format
- Importing the model in Bladed and adding the RNA
- Running all the analysis in Bladed
- Calculation of the SCFs for the relevant K-joint in accordance with [3]
- Including the SCFs in the stress calculations [3]
- Rainflow counting of the stress time series

- Calculating of the fatigue damage using the Efthymiou principle for 8 hot spots of the relevant brace in the K-joint.

Numerical model

The IDA workflow is shown in Fig. 3 [4]. First, the numerical model of the jacket structure is developed in the advanced offshore code SESAM GeniE. It is then converted into a Bladed format and imported into Bladed (aero-elastic solver), where it is linked to a 10 MW wind turbine based on a realistic reference design [2].

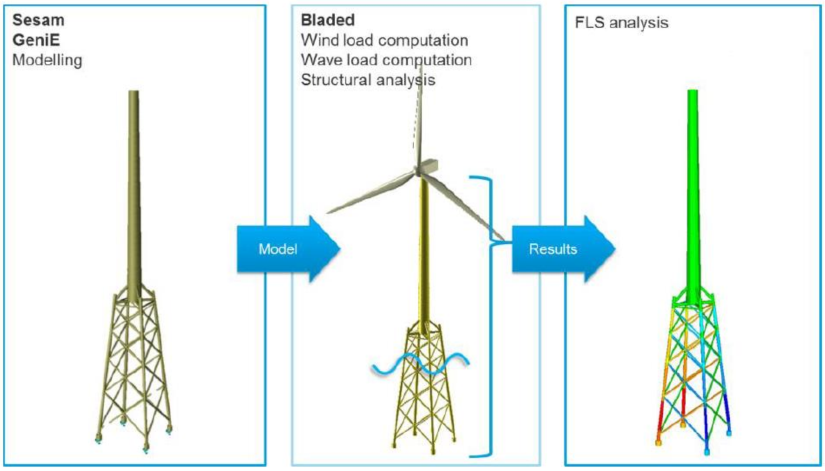


Figure 3. Workflow of the IDA using SESAM and Bladed [4]

The jacket structure is designed for an offshore site with water depth of 50m. It is supported by four piles 40 m embedded in the soil, which are here modelled by means of springs with the equivalent stiffness. The footprint disposition is 34 x 34 m. The RNA has a rotor diameter of 178.16 m with a hub height of 118.38 m (Fig. 4).

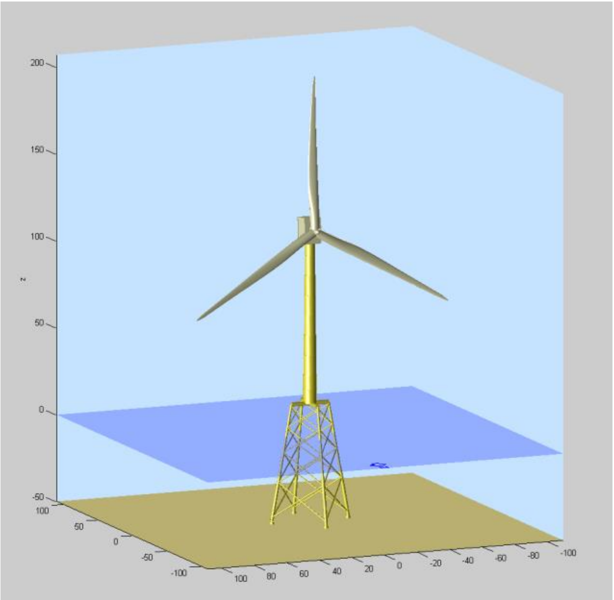


Figure 4. Numerical 3D model of the jacket structure with tower and RNA in Bladed

Loads

The jacket structure is exposed to wave loads and to wind loads mostly transferred from the tower with an RNA.

OWTs, as slender structures with a significant dynamic response, require stochastic modelling of the wave kinematics by means of irregular sea states. A sea state is defined by a wave-energy spectrum with a given significant wave height, a representative wave peak period, a mean propagation direction and a spreading function. Authors refer to [9] for a detailed explanation on modelling of irregular sea states in OWT design.

Regarding the realistic data, the mean wind speed for the target offshore site is 10 m/s. The wave energy spectra characteristics, namely significant wave height and mean zero-up crossing period, depend on the mean wind speed and in this case their values are respectively H_s=1.38 m and T_z=3.87 s. The irregular sea state is generated in Bladed and simulated 10 mins with a time step of 0.05 s. The whole process is repeated 6 times, each time changing only the randomness factor of the irregular sea state. That way, six different sea states with the same main characteristics are simulated and the fatigue damage is separately calculated for each simulation.

Wind loads are modelled by a turbulent wind field, where the basic idea is to describe spatial and temporal fluctuations with relevance for wind turbine load calculations. The turbulence has a three dimensional structure described by a spectral tensor. For a spectrum type, that describes the variance of the wind velocity fluctuations, Mann’s model is chosen here, due to its good applicability for the flat, homogeneous terrains such as the sea surface. The main idea of this model is a division of the wind flow into a mean and a fluctuating part. For more detailed explanation about the Mann’s model of the wind turbulence, authors refer to [10].

The Bladed software has a subprogram that defines the wind turbulence, once having all the wind turbine input parameters (dimensions of the wind field that covers the whole rotor area, simulation duration, main wind speed, height where the main wind speed is captured – hub height). The defined turbulence is an output file (.wind file) of this subprogram. Afterwards it used as an input file that defines wind loads in the final wind-wave simulation. In the similar manner as for the wave loads, six simulations have been carried out. In each simulation, different .wind file is used as a wind loads input file. Each of them six is created by the subprogram where the turbulence is defined with the same main characteristics, only the turbulence seed number is changed. The fatigue damage is here again separately calculated for each simulation.

To include the uncertainty caused by the stochastic nature of the wave and wind conditions, the final fatigue damage is taken as the mean value of the six separately calculated values.

The output of the simulations in Bladed are load time series. Comparing the loads in the members of the jacket structure, the most affected K-joint is chosen as the relevant one for this research. The most loaded K-joint is one the lowest four K-joints, as shown on the Figs. 5~6.

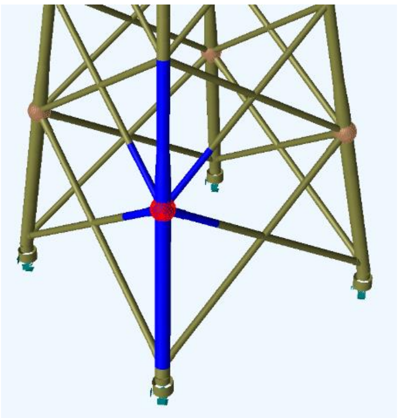


Figure 5. The most loaded K-joint of the jacket structure

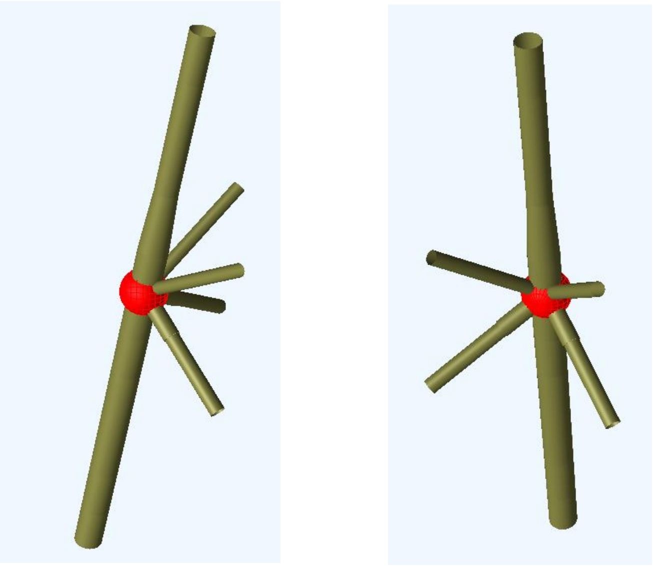


Figure 6. Detail of the reference K-joint

Since the stress time series are needed for a fatigue damage calculation, stresses are calculated by a channel combination of load series, using the Eqs 1-8 from [3]. These formulas include the stress concentration factors (SCFs) for tubular joints. Those are calculated in terms of Efthymiou principle. It considers the geometry of the joint and the type of loads applied. For the K-joints, SCFs for tubular joints are calculated as given in the Appendix B of the DNV GL-RP-C203 [3].

Once the SCFs, as well as the loads (F_x, M_y, M_z), are known, the stresses of the reference K-joint are calculated in terms of hot spot stresses. Figure 7 shows the hot spots locations on the brace circumference where the stresses are calculated, as well as the superposition of loads in the element in order to get the stresses. In each simulation, the highest of eight hot spot stresses is taken as the relevant one.

$$\sigma_1 = SCF_{AC}\sigma_x + SCF_{MIP}\sigma_{my} \tag{1}$$

$$\sigma_2 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x + \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} - \frac{1}{2}\sqrt{2}\,SCF_{MOP}\sigma_{mz} \tag{2}$$

$$\sigma_3 = SCF_{AS}\sigma_x - SCF_{MOP}\sigma_{mz} \tag{3}$$

$$\sigma_4 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x - \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} - \frac{1}{2}\sqrt{2}\,SCF_{MOP}\sigma_{mz} \tag{4}$$

$$\sigma_5 = SCF_{AC}\sigma_x - SCF_{MIP}\sigma_{my} \tag{5}$$

$$\sigma_6 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x - \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} + \frac{1}{2}\sqrt{2}\,SCF_{MOP}\sigma_{mz} \tag{6}$$

$$\sigma_7 = SCF_{AS}\sigma_x + SCF_{MOP}\sigma_{mz} \tag{7}$$

$$\sigma_8 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x + \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} + \frac{1}{2}\sqrt{2}\,SCF_{MOP}\sigma_{mz} \tag{8}$$

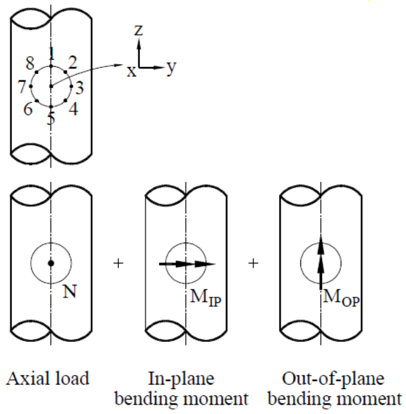


Figure 7. Hot spots and superposition of stresses in K-joint [3]

Now that the stress series for each of the six simulations are obtained, the next step for the fatigue calculation is to do a rainflow counting in order to get the number of cycles in the correspondent stress ranges.

Once the rainflow counting is done and the number of cycles are attributed to the corresponding stress ranges, fatigue damage of the K-joint is calculated by means of Markov matrices [8]. For the calculation of the fatigue damage, an S-N curve for the structures in the seawater with cathodic protection from DNV GL-RP-C203 is used (Fig. 8).

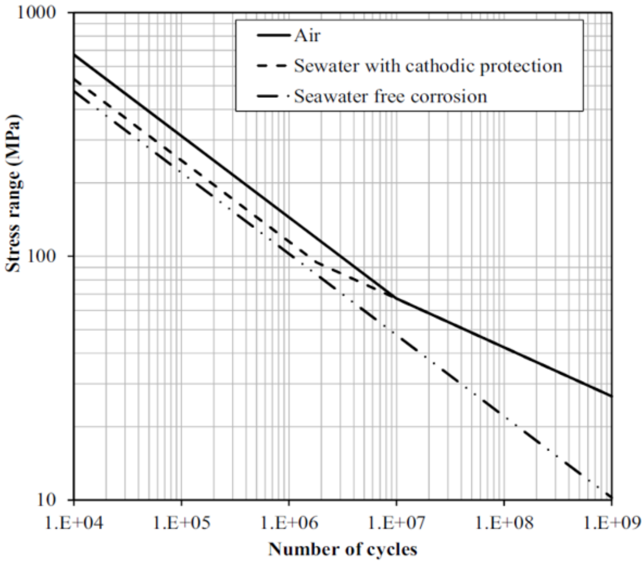


Figure 8. S-N curves for tubular joints in air and sea water with cathodic protection [3]

As mentioned, the final fatigue damage that represents the IDA is taken as a mean value of six fatigue damages obtained through six simulations where the random factor of the irregular sea state and turbulence seed number took six different values.

3. RESULTS

Six simulations were carried out, where six different wind seeds and sea state randomness factors were used. Each simulations includes applying the coupled wind and wave loads on the FE model, which is now consisting of the jacket structure, tower and an RNA, making a unique system that withstands the defined loads. Once the stress time series are obtained, the rainflow counting has been conducted using the feature of Bladed. Thus, the ranges of stresses with the corresponding numbers of cycles are obtained. The calculation of the fatigue damage from Markov matrices gave the following results, where $\boldsymbol{D_{max}}$ stands for the highest of eight hot-spot stresses pro simulation (Table 1). The final fatigue damage is a mean value of six simulations (Eq. 9).

Table 1. Fatigue damage of the relevant K-joint

Simulation	$\boldsymbol{D_{max}}$
1	1.355
2	1.232
3	0.972
4	1.051
5	1.081
6	1.616

$$\overline{D} = \frac{1}{6}\sum_{i=1}^{6} D_{max,i} = 1.218 \tag{9}$$

4. CONCLUSIONS

The examined procedure for the FLS analysis and the fatigue damage calculation proved to be less complicated and faster compared to the alternative. The IDA combined with the hydro-aero-elastic solver Bladed benefits from lower computational costs, concerning that it runs all the simulations simultaneously, without duplicated simulations in different codes. An optimised and verified compatibility of Bladed with an offshore code SESAM gives options for more detailed modelling and coupling. The next steps in the research are to carry out the same case analysis in SDA in order to closely perceive the difference in the results, methods and computational costs.

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