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CURRENT DEVELOPMENTS OF SUPPORT STRUCTURES FOR WIND TURBINES IN OFFSHORE ENVIRONMENT

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ABSTRACT

Support structures of Offshore Wind Energy Converters (OWECs) are exposed to combined loading from wind and waves. Therefore the fatigue damage evaluation is an important part in the design phase of offshore wind farms.
Different design concepts for offshore support structures at sites in North and Baltic Sea are presented. Traditional concepts for fatigue design vary from deterministic methods, which have been adopted from experiences in the design of oil and gas platforms, to calculations in the time domain, which are applied to the actual generation of multi megawatt onshore wind energy converters. Choice of the appropriate method is less based upon the type of structure than upon the site specific environmental conditions.
For tripod structures the fatigue strength of tubular joints is determined by local approaches. Besides the structural stress approach, sophisticated concepts like the notch stress approach can be used for fatigue assessment. The notch stress approach combines a better insight in the damage mechanisms with the potential of optimising welded structures.

KEYWORDS

Offshore, Wind Energy, Support Structure, Fatigue, Local Concepts

INTRODUCTION

Within the last years wind energy industry in Europe has developed fast and is nowadays an important branch of the economy. More than 28000 Megawatts (MW) of capacity have been installed in Europe by the end of 2003 with yearly growth rates above 20%. Within Europe Germany plays a significant role, more than half of the total capacity has been installed there. Therefore actual developments in Germany are somewhat representative for future trends in other countries. As economically profitable locations for land-based wind farms are becoming rare, a study by Johnson (2004) has shown that the new challenge for wind energy – besides the "re-powering" of old wind farms - lies offshore.

Current experiences with offshore wind energy are limited to quite a few European countries. With a doubling of total capacity the year 2003 has shown an important step forward in offshore installations. By the end of 2003 about 16 near- and offshore wind farms have been installed with a total capacity of 530 MW, mainly in Denmark.

SUPPORT STRUCTURES

Foundation Concepts

Offshore projects require initially higher investments than onshore projects. According to the actual distribution of capital investment costs a stake of 20-25% has to be spent for the support structures and their installation.
The future offshore wind energy converters (OWECs) will be provided with turbines of a capacity between 3 and approximately 5 MW. The turbines are mounted on steel tube towers, which is the standard onshore solution. Due to the better wind conditions with higher mean wind speeds and a reduced surface roughness the hub heights can be reduced to about 80 m.
Concerning the wind farms planned in the so-called Exclusive Economic Zone of Germany in North and Baltic Sea most of the support structures will be located in regions with water depths between 20 and 50 m. For these water depths, different types of support structures are currently under discussion.

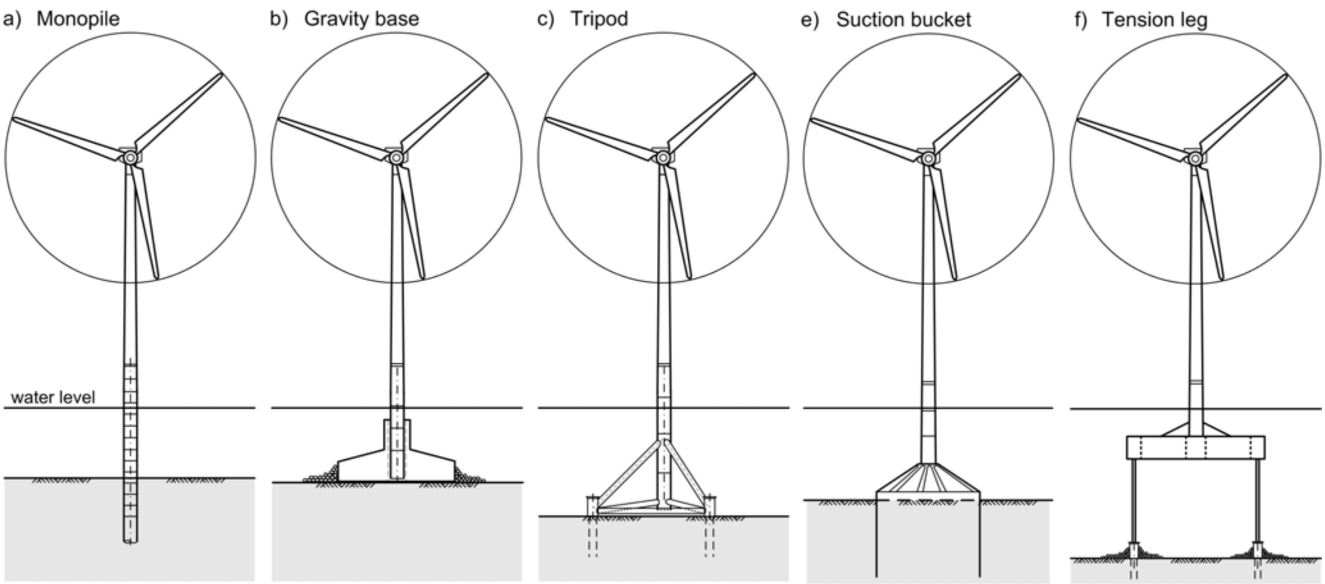


Figure 1: Concepts for the support structures of offshore wind energy converters

The so-called monopiles (Figure 1a) are effectively an extension of the steel tower, driven or drilled into the seabed. They are used extensively in the off- and nearshore environment for supporting oil and gas platforms and other coastal structures. To some extent the monopile can be considered as the state of technical knowledge, reflecting the current design philosophy for medium water depths (up to 20 m). Gravity-based foundations, either blocks (Figure 1b) or caissons, are designed with a flat base to resist the overturning forces. Caisson types are typically made of steel or concrete and can be ballasted with water, iron or various grouted materials.
So far only monopile and gravity base support structures have been used for the installed wind farms, which are located in small water depths predominantly between 5 m and 15 m. For future projects with higher water depths other structures are proposed, mostly drawing on designs already in use in other offshore sectors. Possible concepts are shown in Figure 1c-e. Braced towers can be realised as tripods, discussed by Schaumann & Kleineidam (2002), or lattice towers like the jacket solution. Thus the tripod supports a central tube which extends into the tower, with each corner of the tripod support piled

into the seabed. The jacket can be any of a variety of arrangements whereby a central tube is surrounded by numerous piled supports. Suction-based foundations have also been proposed, replacing the pile. An inverted ’bucket’ forms the foundation to which suction is applied until it penetrates to the desired depth. The tension leg system is a submerged floater with tensioned vertical anchors. Advantage of this new concept is its simple installation – the structure can easily be towed to the site – and its applicability for a wide range of water depths.
An approximate classification of the different types of support structures regarding the water depth is done by Schaumann et al. (2004). Anyway it should be pointed out that there are other parameters with great impact on design and optimisation of the support structures, as Figure 2 shows.

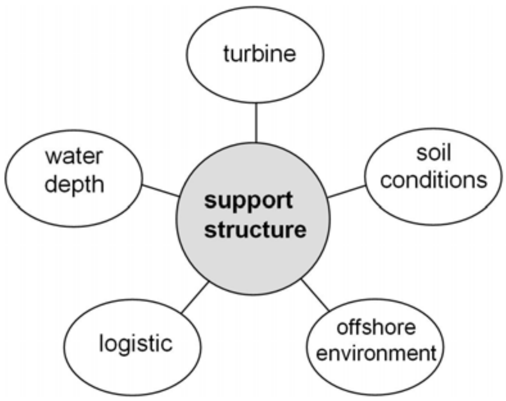


Figure 2: Design drivers for OWEC’s support structures

As a rule of thumb, based on experiences with the already completed wind farms and preliminary design calculations done by the authors, the required amount of steel for an entire structure (foundation and tower) is in the region of 1000 tons. Considering only the future German plans with predicted 8000 OWECs to be installed until 2030 it will lead to a noteworthy steel consumption by the offshore wind energy industry.

FATIGUE DESIGN

Design Approaches

Support structures of offshore wind energy converters are exposed to combined loading from wind and waves. Speaking in terms of fatigue assessment the turbulent wind and the unsteady sea state lead to high dynamic loads with a number of cycles of about 10^9. Various calculations by the authors show that for structural parts below water level the fatigue assessment governs the design. With increasing rotor diameter and turbine mass the wind loads tend to dominate, while for small turbines the wave loads outweigh. Simplified approaches for combination of wind and waves exist but integrated models are effectively state-of-the-art. Nevertheless integrated simulation software, which is capable of including complex structures like tripods, is rare. For the fatigue assessment of offshore structures under wave loadings several approaches exist (Figure 3). The deterministic approach, widespread in offshore industry, uses a discrete wave analysis in combination with site specific wave height exceedance diagrams. Inaccuracies are mainly founded in the definition of the relationship of wave height and period and the simplification of dynamic effects assuming a quasi-harmonic excitation. Time domain simulations in contrast use a number of sea state dependent time series with corresponding wave loads which are used as input for time history calculation as shown by Schaumann et al. (2003). The third method calculates the structural response in the frequency domain, self-evident as wave spectra are naturally described in frequency domain, leading to the problem that damage evaluations also have to been done in the frequency domain. Connection of time and frequency domain results in a so called hybrid approach, which combines the accuracies of the time history analysis with the savings in computing time of frequency based calculations. A detailed description of the different approaches and the software tools developed at the Institute for Steel Construction of the University of Hannover is given by Kleineidam (2004).

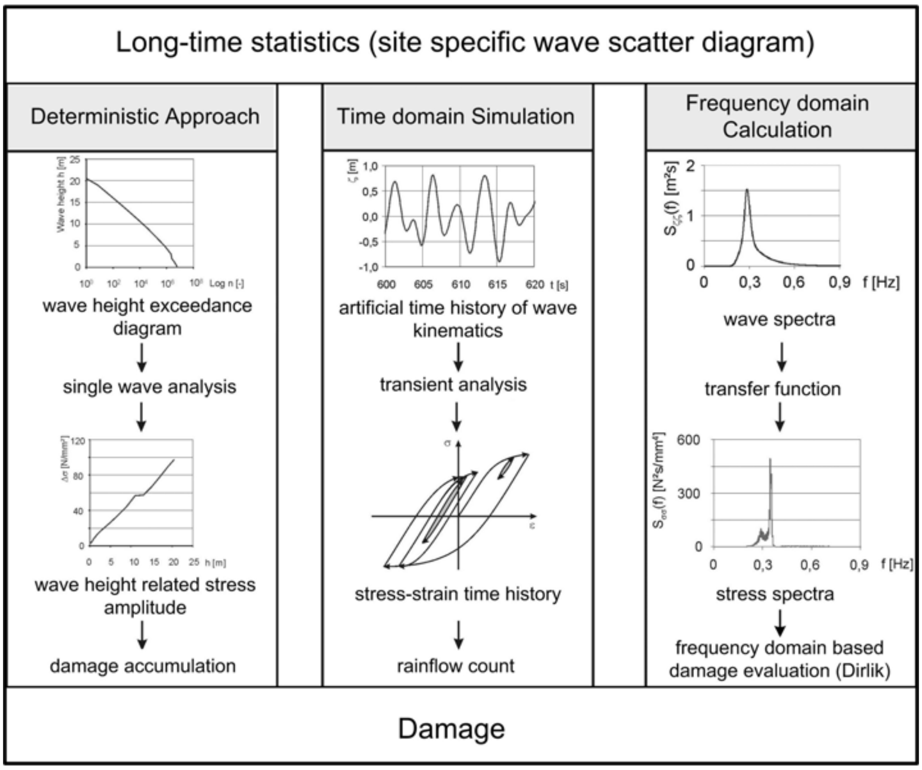


Figure 3: Fatigue design approaches

The different approaches have been compared for monopile systems, using identical numerical models and water depths. Wave load calculations are based on linear wave theory with corrections according to Wheeler (1970). The generation of the wave load time series has been done using the PIERSON-MOSKOWITZ-spectrum. Two different sites have been considered with different long time wave statistics as shown in Figure 4. For Baltic Sea conditions it should be noted that the peak of probability lies within the range of the first eigenfrequency of the structure (which usually is adjusted between 0.3 and 0.4 Hz for three-bladed turbines).

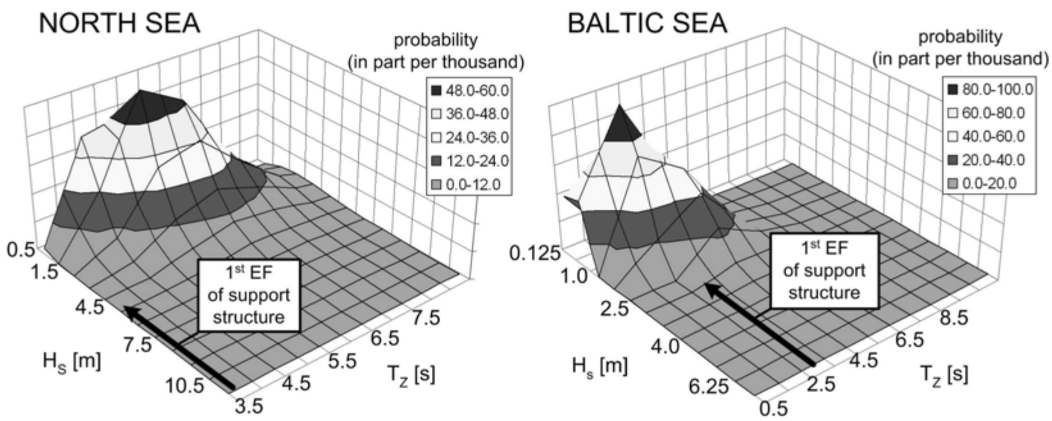
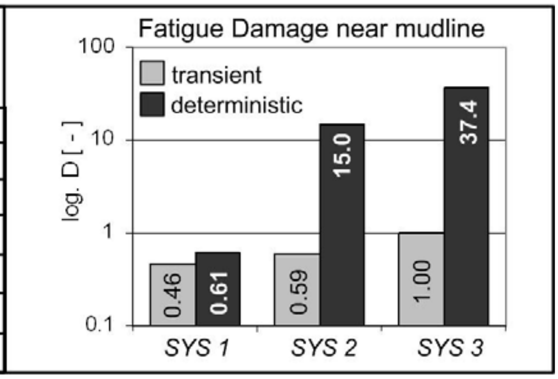


Figure 4: Wave scatter diagrams for two different locations

The main features of the monopile support structures are shown in Table 1. The towers are equipped with a small turbine, thus wave loads outweigh the fatigue assessment. Calculation of fatigue damage from sea state both for time domain and deterministic approach shows two characteristics. According to the underlying wave scatter diagrams the fatigue damage in North Sea condition is expected to be smaller, as only few waves are in the range of the eigenfrequency of the structure. Both approaches lead to almost identical damages. For the Baltic Sea locations the deterministic approach gives much higher damages compared to the transient analysis. Here the simplified calculation of the dynamic response has a great influence, which is confirmed by the enormous increase in damage caused by the small shift in eigenfrequency between System 2 and 3. If there is a significant number of sea states with mean periods near the natural period of the structure, the deterministic approach is too conservative and should be used with caution.

TABLE 1
FEATURES AND RESULTS OF THE ANALYSED MONOPILE STRUCTURES

Monopile Support Structure			
water depth = 25 m			
hub height = 70 m			
m_{top} = 100 t			
-	Location	Soil type	1[st] Eigenfreq.
SYS 1	North Sea	non cohesive	0.36 Hz
SYS 2	Baltic Sea	non cohesive	0.36 Hz
SYS 3	Baltic Sea	cohesive	0.31 Hz



Fatigue Assessment by Local Concepts

For monopile structures the nominal stress approach may be used to calculate the damage values for most of the tower details. For the joints of braced or lattice structures with its large variety of potential geometries the nominal stress approach can hardly be applied. Local concepts according to Figure 5, described by Radaj & Sonsino (1998) in detail, must be applied. The use of the structural stress approach for tubular joints is state-of-the-art and part of all actual offshore standards (Germanischer Lloyd (1995), NORSOK (1998)). A description of this so called hot-spot-method is given e.g. from Puthli (1998). Although not part of the standards, a more sophisticated local approach, the notch stress approach, can be adopted successfully.
As it is general practice to design the structures against technical crack initiation, the work within the research project ForWind has been focussed on the two local approaches mentioned above.

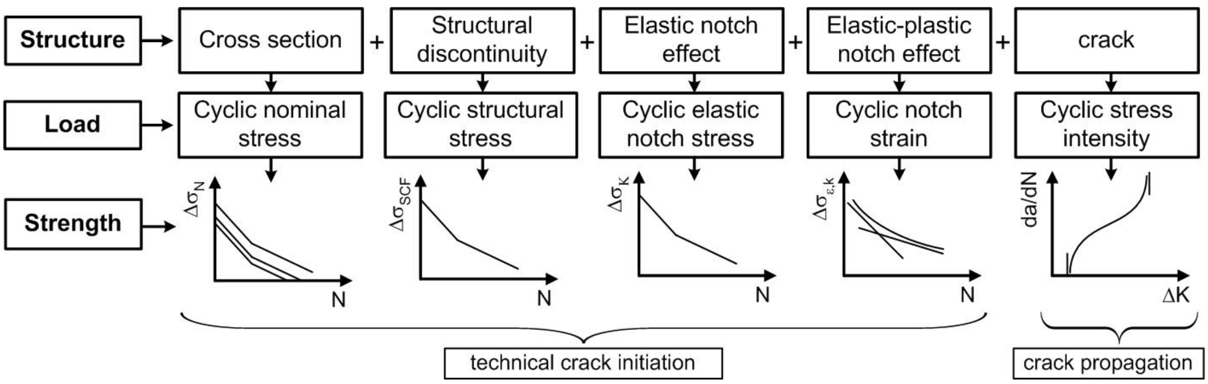


Figure 5: Approaches for fatigue assessment

Research has shown that stress concentration factors (SCF) for the hot-spot method should be determined by finite element analysis with volume elements. If shell-elements are applied compensation for weld zone stiffening is time-consuming and stresses extrapolated to the midline intersection lead to conservative results. On the other hand SCF from parametric expressions can lead to non-conservative designs. Furthermore complex joints, their three-dimensional loadings and special boundary conditions, for example in tripod structures acc. to Figure 1, can hardly be compared to simple tubular joints. Efthymiou (1988) presents a simplified method for arbitrary non-planar tubular joints using influence functions. In Figure 6 results of comparative calculations are presented, using the simplified approach according to Efthymiou and a detailed calculation with a volumetric finite element model. The Figure shows the related amplitude stress range for a top tripod node within the range of typical dimensions. Linear waves with different angles of attack μ have been used. While for the crown location the compliance is well, the saddle location, which is usually the governing design point, shows differences of about 15%. A combined method, the series named "EFT + FEM" (SCF according FEM combined with Efthymiou's influence function), points out, that the influence functions itself cannot be applied to tripod joints.

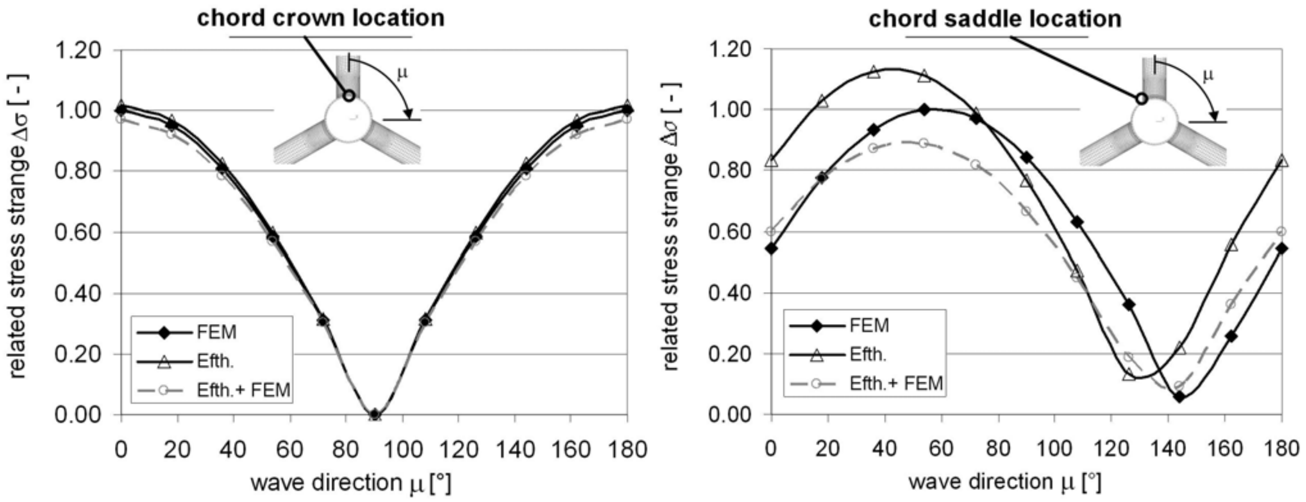


Figure 6: Comparison of different methods for the fatigue evaluation of tripod joints

If spatial wave fields are introduced, as shown by Schaumann et al. (2004), a too penalising design can be avoided. For braced structures like tripods, the directional transfer function (Figure 6) obviously differs from that of a monopile. Thus it leads to a much smaller reduction in damage of about 30% if wave spreading – either based on site specific data or artificial functions (e.g. the cosine-power-law) – is considered. Due to the dominating influence of the aerodynamic damping of the OWECs more knowledge of the correlation between wind and waves has to be gained before wave spreading effects should be taken into account.

The notch stress approach is applied according to the engineering approach of Olivier et al. (1994). A fictitious notch radius ρ_f proposed by Neuber (1968), which takes microstructural support effects of sharp notches into account, is given by Eqn. 1. Based upon that Radaj (1985) developed a worst case scenario, introducing the real notch radius ρ as zero. With a microstructural support length ρ^* (~0.4 mm) and a factor s of 2.5 for mild steels this leads to a fictitious radius of 1 mm. Because of the requirements in the element mesh at the notch (element sizes between 0.1 and 0.25 mm), sub-modelling techniques have to be used to reduce the degrees of freedom. Thus computing time is much higher compared to the hot-spot method.

$$\rho_f = \rho + s\,\rho^* \qquad (1)$$

Extensive tests along with parametric finite element studies, documented by Olivier et al. (1994), led to the development of notch stress S-N-curve with a reference value of the fatigue strength at 2 million cycles of 225 N/mm² (FAT 225). The applicability of this approach to tubular welded joints of offshore structures was proven by own investigations. Figure 7a shows the resulting lifetimes of a series of calculations compared to the hot-spot method. Simplifying a constant stress range of 10 N/mm² has been applied, accounting for axially loaded braces and out-of-plane bending. The S-N-curve for the structural stress approach (FAT 100) and the plate thickness effects have been assumed according to Germanischer Lloyd (1995). The weld profile was modelled with the gross weld section as defined by AWS (2000). With an average deviation of 35 % the correlation is well compared to the usual scatter expected in lifetime predictions.

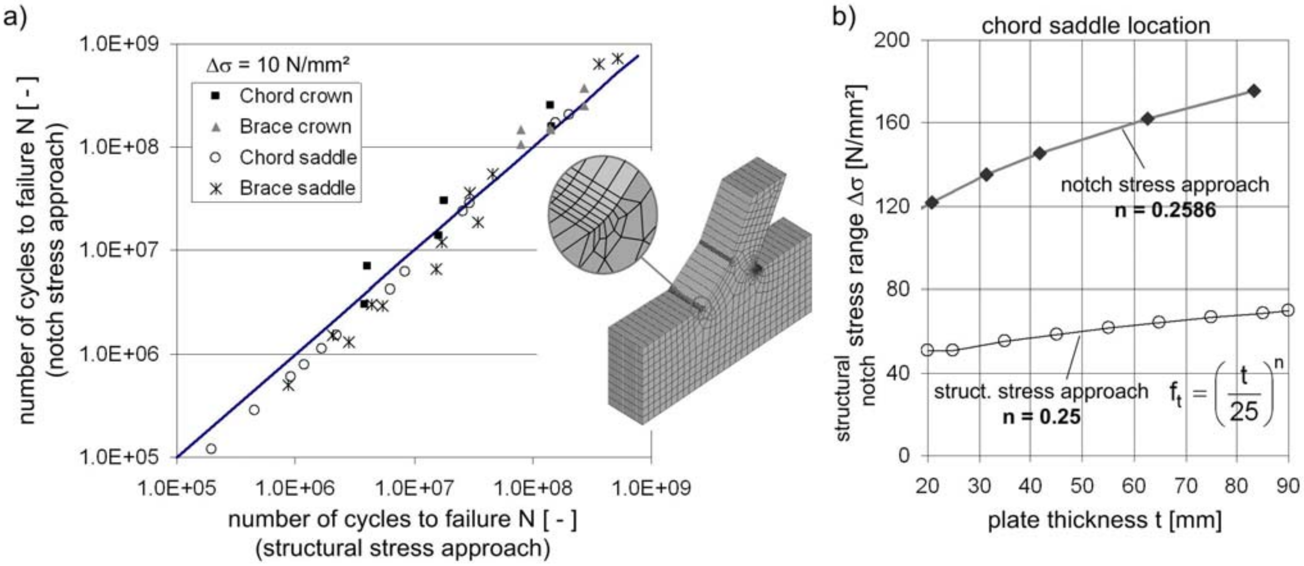


Figure 7: a.) Endurable number of cycles for the structural stress and the notch stress approach (Y-joint, D_{chord} = 4000 mm, slenderness ratio γ = 24, inclination θ of brace is variable)
b.) Comparison of plate thickness effects for a typical Y-joint

Furthermore the notch stress approach allows more detailed research into parameters with impact on the fatigue strength, e.g. flank angles at the weld toe or plate thickness effects (Figure 7b).

CONCLUSION

The damage evaluation of support structures of offshore wind energy converters often governs the design. It has been shown, that the deterministic approach for structures under wave loading should be used with caution, especially if there are a significant number of sea states with mean periods near the natural modes of the structure.
From the presented types of support structures, the braced ones, e.g. tripods, are likely to be used in water depth of 30 m or more. The fatigue assessment of the tubular joints of these structures must be done by local approaches. The complexity of the problem usually requires the application of finite element methods. Simplified approaches, like the one presented by Efthymiou, should be used with caution. Besides the hot-spot method, it is shown that the notch stress approach leads to reliable results for welded offshore members. Moreover this concept allows a deeper insight in the damage mechanisms. The robustness of the underlying model expands its range of application to cases, where the structural stress approach is not validated.

ACKNOWLEDGEMENT

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