Fatigue design of support structures of Offshore Wind Energy Converters

Prof. Dr.-Ing. Peter Schaumann; Dipl.-Ing. Patric Kleineidam; Dipl.-Ing. Frithjof Marten
Institute for Steel Construction
University of Hannover
Appelstr. 9A; D-30167 Hannover; Germany
Tel: +49-511-762-3781; Fax: +49-511-762-2991
schaumann@stahl.uni-hannover.de; www.stahlbau.uni-hannover.de

1 Situation of Wind Energy in Europe

The development in wind energy within the last 15 years is tremendous. By the end of 2003 more than 28.000 MW of capacity have been installed all over Europe, see Fig. 1. Within Europe Germany plays a significant role, more than half of the total capacity has been installed there. About 15.400 wind turbines with very different rated power are in use. They produced over 5% of the electricity needed in the year 2003. In some of the federal states at the coast (e.g. Schleswig-Holstein) the percentage is up to 25%.

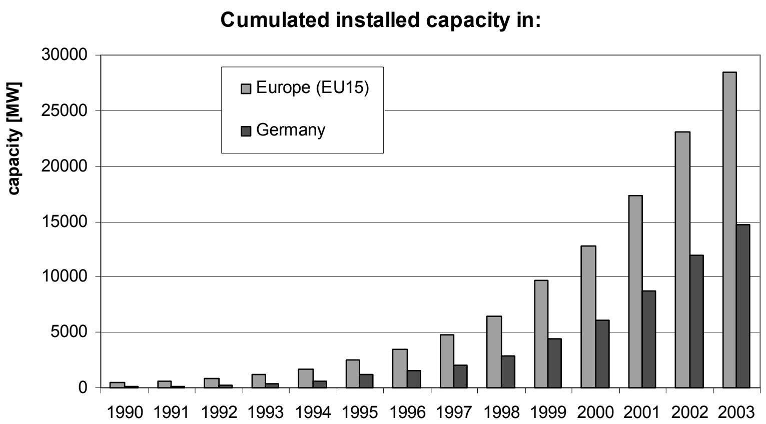


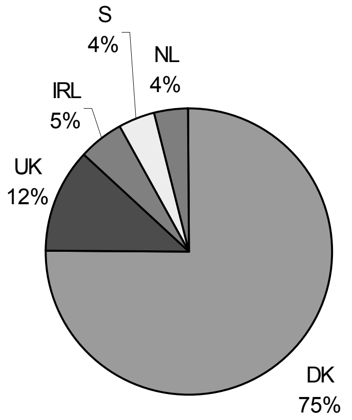
Fig. 1: Trend of the cumulated installed capacity in Europe (EU15) and Germany source: www.ewea.org and www.wind-energie.de

The history of wind power generation is young. Nobody could have ever imagined the development of the last 15 years. Also until the late nineties the construction industry has not taken this market really serious. Just ten years ago the average capacity of wind turbines was only about 350 kW. This is only 10 % of the capacity, which the biggest turbines installed in Germany have today.

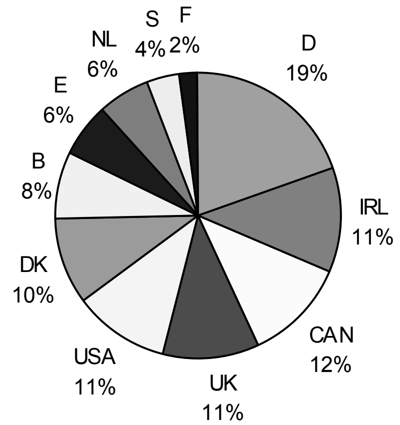
The impressing development of wind energy in the last years is mainly caused by the power input law released in Germany 1991. This law committed the energy producer to induct the wind energy power in their grid and to pay 9,1 cent/kWh for it. In 2000 the power input law has been displaced by the "Renewable Energy Law" (EEG), which is currently under revision. Many other countries like France, Spain, Greece or Brazil are since following this example of a legal regulation.

Only a few European countries, Denmark, Sweden, Great Britain, Ireland and the Netherlands have so far experiences with the construction of offshore wind parks, as the left diagram in Fig. 2 shows. With 75 per cent of the installed offshore capacity worldwide Denmark clearly leads the field. The wind park "Horns Rev" (see Fig. 3), erected in 2002 with 80 monopile-founded converters and a nominal capacity of 2 MW each, is also the largest wind park in the world by now. The wind park "Rødsand", operating since 2003, has nearly the same size with a total installed capacity of 158.4 MW. Both parks are Danish. The biggest offshore converters are installed at "Arkolw Bank" with a capacity of 3.6 MW each machine. Seven of the 200 planned converters are operating in the Irish Sea up to now. All offshore farms are operating in moderate water depths of less than 10 m with the only exception at "Horns Rev", which is located 14 km offshore at water depths of about 15 m.

A forecast for the year 2006 (see Fig. 2, right diagram) shows that the situation in offshore wind energy is supposed to change. Denmark will probably loose its supremacy and a more uniform distribution is expected. Countries like the USA, Canada and Germany, which do not have realised any offshore wind park yet, could reach remarkable shares.



a) 2003: 530 MW offshore installed



b) 2006: 3960 MW offshore expected

Fig. 2: Stake of the countries worldwide in installed offshore capacity - left diagram: 2003; right diagram: forecast to the year 2006; source: Sonne, Wind und Wärme 3/2004

German plans for the future are tremendous. In the forthcoming decades huge wind parks shall rise in the North- and Baltic Sea. According to an estimation of the German Wind Energy Institute (DEWI) the total capacity of these parks shall be up to 25.000 MW [1]. The dimension of a single converter is expected to be in the range of 3 to 5 MW to make the investment cost-efficient, if the farm is planned in water depths of about 30 m and far away from the coast outside the 12-seamile-zone – the so-called exclusive economic zone (EEZ).

Fig. 3 Windpark Horns Rev, erected 2002; source: Vestas Germany

2 Structural Development

For onshore wind turbines steel tube towers have been accepted as the standard tower type. This construction, in association with a solid foundation, emerged as the optimum for safety and economy for nearly 10 years. Only temporarily one- or two-piece pre-stressed concrete towers were used for comparatively small converters with heights up to 40m. The development into the megawatt-class led to higher loads and greater heights of the tower. Attention should be paid to the requirements on the dynamic properties of the tower construction, which must be co-ordinated with the turning rotor blades concerning the natural modes. A statistic evaluation of 68 wind turbines in the megawatt-class (see Fig. 4, data from [5]) showed, that the tower weight of steel tube towers, referred to hub height and nominal output, lies approximately at 1 t/m/MW. Thereby this referred weight slightly decreases with increasing rated power. A steel tower of a 2 MW-converter with a hub height of 100m is expected to weigh about 200t.

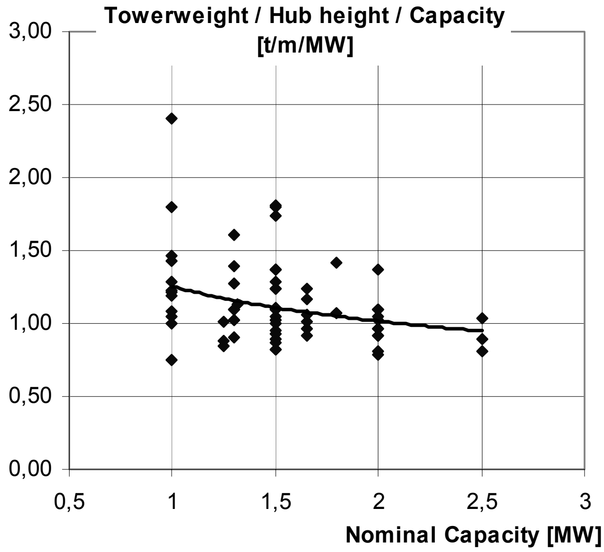


Fig. 4 Referred weights of steel tube towers of 68 wind turbines in the MW-class; source: Windkraftanlagenmarkt 2002 [5]

Increasing tower heights lead to increasing diameters of the lower tower segments. This causes transportation problems concerning the headroom at bridges (4,50m). As an alternative to tubular towers the steel construction industry has rediscovered the lattice tower for wind turbines. The highest wind turbines built in Germany at present have been realised according to this design. Recently so called hybrid towers have been developed for onshore application comprising a pre-stressed concrete part at the bottom and a tubular steel part on top of the tower

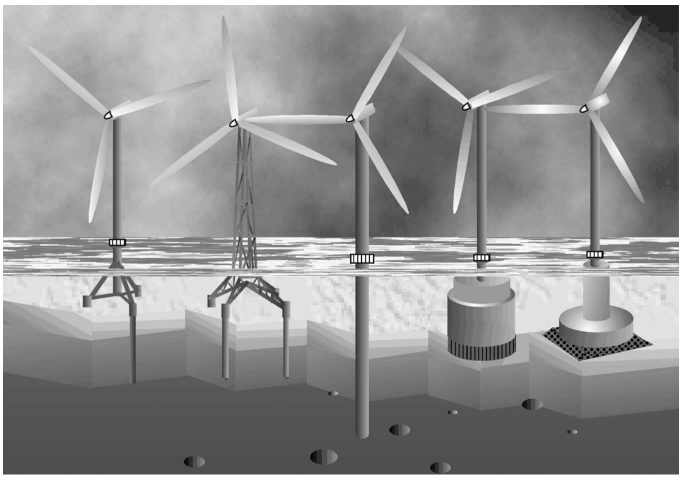


Fig. 5: Concepts for support structures for offshore wind turbines © GIGAWIND

In the offshore sector there is no limitation of the diameter to steel tube towers, if the fabrication is sited directly at the coast. The most-economic construction for support structures for offshore wind turbines is depending on three major parameters: water depth, soil conditions and rated power of the turbine determining height and diameter of the tower [11]. Possible foundation concepts are shown in Fig. 5. Recently erected offshore wind parks predominantly have monopile- (Fig. 5, middle) and in one case gravity based foundations (Fig. 5, right); see also [9]. But it is foreseeable, that there will be more than one option for the type of construction (see also [11]). A research project funded by the German Federal Ministry of Economy is devoted to this topic, which is carried out by four institutes at the University of Hannover within the work group GIGAWIND. The Institute for Steel Construction is member of this working group.

3 Offshore Structures for Wind Energy Converters

3.1 General

Towers of wind turbines are the support structure of the machine, consisting of the rotor, generator and other components. The task of the tower is to take and carry over the reaction forces of the machine. Because of the dominance of the machine, the loadings of wind turbine towers differ clearly from other towers, i.e. of chimneys and antennas. Very high dynamic loads with number of load cycles over 10^9 have to be expected. These problems lie above the common field of experience in civil engineering. Components with load cycles of this magnitude can hardly be analysed with experimental methods in laboratories. Thus, an important field of recent research is the development of improved fatigue design methods.

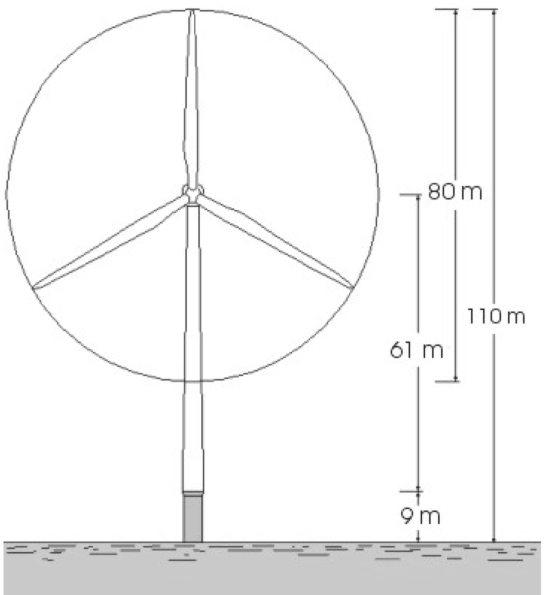


Fig. 6 Dimensions of the wind turbines in Danish Horns Rev www.hornsrev.dk

The structural design of the offshore wind park „Horns Rev“ erected in the year 2002 (dimensions see Fig. 6) was still quite similar to onshore wind turbines. The main difference consisted in the foundation, which is a driven monopile with a diameter of about 4m and 50 mm in wall thickness, and in the transition piece between driven pile and tower. A so called “Grouted Joint” connection has been used. In this special connection two steel pipes with a defined gap are put into each other. The interspace between the pipes is filled with grout. The tower above sea level traditionally consisted of two pile-segments, which were bolted together with ring flange connections. It is obvious, that for the installation of the tower specific ships and lifting isles have to be used. Furthermore the difficult environmental conditions at sea demand particular requirements of the job safety and logistic.

In the following paragraphs some particular aspects of the stability and especially the assessment against fatigue are discussed. The question of the sufficient service strength is connected to the sub questions, which loadings during the lifetime of the wind turbine occur and how the fatigue assessment for different details should be carried out. The loadings result from the unsteady impact of the wind on the rotor, which is forwarded over the nacelle of the turbine to the tower, and the wave loads. The operational loads are influenced by the control parameters of the turbine, a significant example is the pitching of the blades. Also the rate between the rotational speed and the natural mode of the tower is important. According to [2] the operation of the wind turbine is not allowed, when the natural mode of the tower lies in the range of the rotor speed or in the tower-passing frequency of the rotor. Studies to the individual effects are i.e. discussed by Lange [7]. A focal point of the GIGAWIND-project at the University of Hannover is the determination of the fatigue loadings from the wave loads [8].

3.2 Offshore Structures under Wave Loadings

As previously mentioned, wind turbines are exposed to very high dynamic loadings. For onshore converter these loadings are caused by the wind turbulence and the operation of the generator. For offshore converters additional dynamic loadings occur from the permanent unsteady state of the sea. The combination of these different loadings is an outstanding challenge for the design of offshore wind turbines. A wind turbine is a slightly damped mechanic system, first of all if steel towers are considered. During the operation nameable contributions for the damping are given by the rotor due the aerodynamic damping; see i.e. [6]. For slightly damped systems, a dynamic, frequency dependent load near the natural mode of the system will lead to load amplification. On this account the treatment of the natural mode of a wind turbine structure is an important part of the analysis. For a general treatment mainly the dependency of the natural modes in correlation with further parameters is interesting to evaluate different structures.

Within the scope of the GIGAWIND-project therefore parameter studies to the effects on natural modes for monopile- and so-called tripod-foundations (Fig. 5 left) have been carried out at the institute for steel construction. In Fig. 7 the dependency between the first two natural modes and the scheduled vertical soil springs of a tripod-foundation is shown. The horizontal soil properties have a minor effect on the natural mode. Also the stiffness of the tripod-legs has an inferior effect in comparison with the stiffness of the tower. The displayed analysis based on a pilot study for a 5 MW-turbine in a water depth of about 30 m. For this purpose the environment conditions have been applied, which are to be expected for the wind park-location at "Borkum-West" in the German Bight.

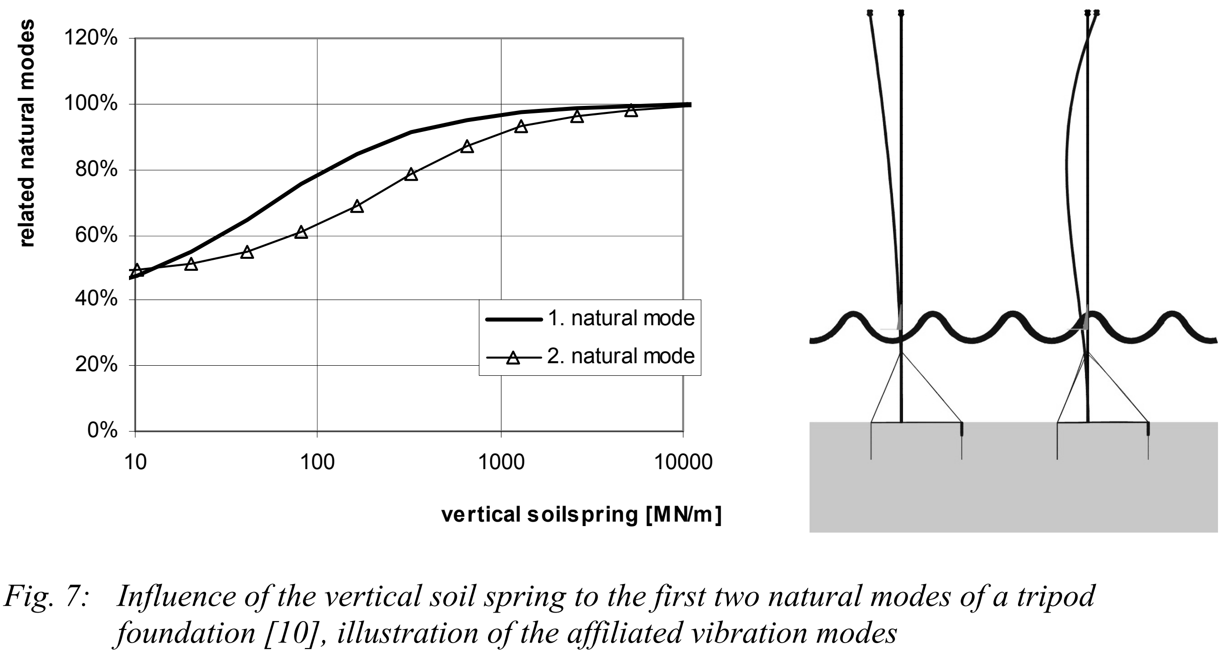


Fig. 7: Influence of the vertical soil spring to the first two natural modes of a tripod foundation [10], illustration of the affiliated vibration modes

For the fatigue analysis of offshore-structures the corresponding guidelines require the anticipation of the stochastic properties of the long term distribution of the sea states, which should be analysed in frequency domain. For Offshore Wind Energy Converters (OWECs), it is state of the art to perform load calculations for wind loading in the time domain. In order to provide an optimal compatibility between wind and wave loading it would be useful to perform time domain analyses for the wave loading as well. Besides the frequency domain, the time domain approach is assumed to deliver the most realistic results. Since calculations in time domain need vast amounts of calculation time, in this paper the use of a deterministic method is evaluated in comparison with time domain calculations. Because of the very short calculation times, the deterministic method seems to be very useful during predesign. For a direct comparison of the methods, results are given for an example with the same characteristics in both cases. The presented work is concentrated on the effects of wave loading, because it is expected that wave loading can be more significant compared to the influence of the fatigue damage of the wind in case of water depth of 30 m and more in North Sea environments.

Software tools have been developed within the research project GIGAWIND to perform the operations that are required by the described approaches. The tools are based on the programmed simulation of the described regular waves and irregular sea states and are combined with a standard FE-program for the solution of the structural response. To compare the described methods for fatigue calculations of OWECs under wave loading in North Sea environment a number of calculations have been carried out. The basic environmental conditions were chosen according to those which can be expected in the area of the first planned offshore wind parks in the German Exclusive Economic Zone and are described in more detail in [8]. Monopiles are considered for the foundation of the example. Different sizes of the wind energy converters are taken into account by variing the top mass between 90 and 320 to. This leads to different diameters of the monopile and different natural modes of the structure.

For reasons of a better comparison between the results, the calculations using the described approaches are done with the same numerical model of the structure, see Fig. 8, and the same theoretical background for the calculation of wave forces. This means, that linear wave theory in combination with wheeler stretching is applied in both cases, see [17]. The deterministic approach has been carried out using the three different methods for the relationship between wave height and period in further figures mentioned as method 1 to method 3. Additionally two different descriptions of the sea-environment have been taken into account, denoted as scatter diagram 1 and scatter diagram 2. The calculations are explained in more details in [16].

The results of the calculations are presented in Fig. 9. Method 2 used for the relationship between wave height and period shows the best results compared to the time domain analysis. It can be noted that the time domain and the deterministic approach show good conformity for the scatter diagram 2. For scatter diagram 1 they show at least the same behaviour even if there are some differences using the different wave height – period relationships.

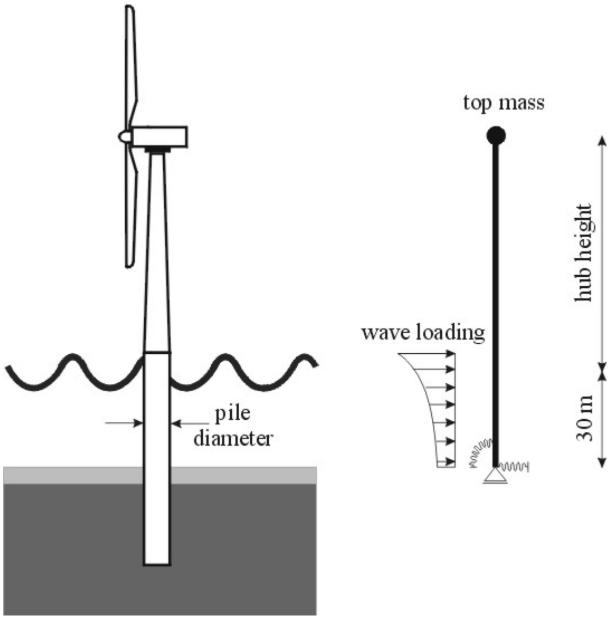


Fig. 8: *Numerical model for calculations*

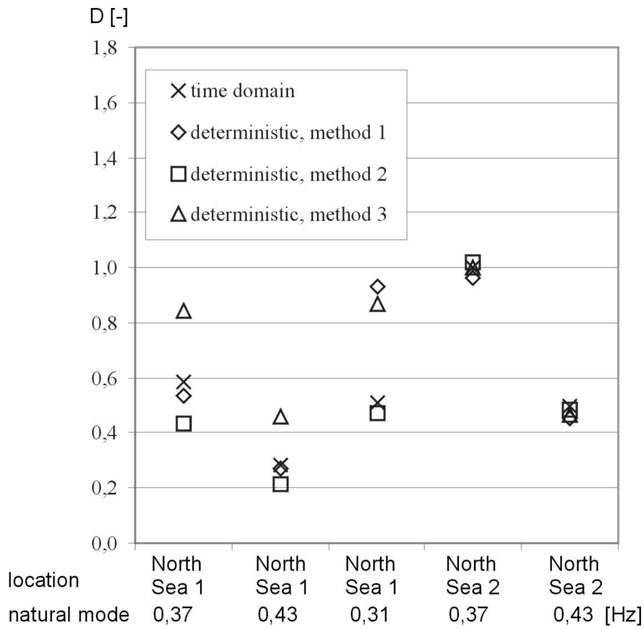


Fig. 9: *Damage values for butt weld for different scatter diagrams, models and approaches*

An explanation for this behaviour can be found in the characteristics of the scatter diagrams. The probability of sea states, whose mean period are close to the first natural period of the structure, is significantly higher for scatter diagram 1. This underlines that the described way of considering the dynamic effects within the deterministic approach is sensitive to the applied method depending on the relationship between wave height and period and should be used with caution. On the other hand, it can give a good hint which role is has the fatigue damage of the waves for the structure with reasonable advantages concerning the calculation time.

3.3 Fatigue Strength

Wind turbine towers and especially the towers of offshore turbines are mostly designed as steel tube towers. These tube towers are pre-fabricated in workshops, then brought to the construction-site and assembled there. The connection between two such tube pieces is normally carried out with ring flange-connections with inner flanges. The fatigue loading in the bolts of such a ring flange-connection is object of intensive research-studies in recent years (see [12], [13] and [14]).

In common calculation-methods the ring flange is reduced to a single segment (see Fig. 10). The further investigations are made on this segment. The bending-load in the tower leads to a cycling pull/push-load in the plate which is connected to the flange segment. The stress in the bolt depends on the load-level in the plate. The correlation is non-linear, because the contact pressure between the flange surfaces decreases with increasing traction in the plate and the connection begins to diverge. The geometric ratio of the flange and the existing pre-load in the bolt has an effect on this process.

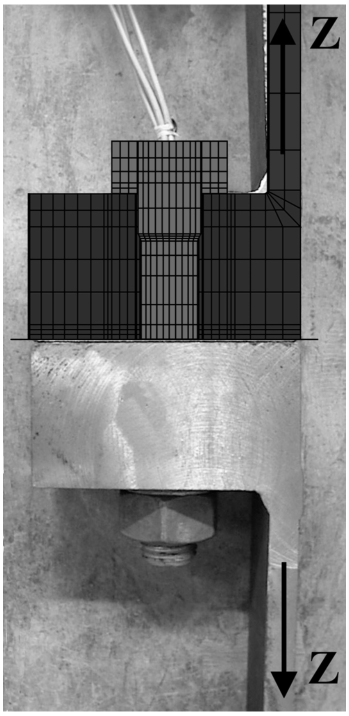


Fig. 10: FE-Model and flange segment

For the analysis of these correlations a research study has been carried out at the Institute for Steel Construction. Herein tests on segments were accomplished in the laboratory and bolt□ with strain gages were integrated into towers of wind turbines. The measured results were compared to FE-calculations [15]. Based on the investigations an analytic method for calculation of ring flanges was developed by Seidel, which is described in [14].

In a research study at the university of Essen large scale measuring tests on complete ring flanges were carried out. Schmidt and Jakubowski analysed in particular the effect of the imperfections on the fatigue-loadings. They pointed out, that especially tube-sided gaps, which only exist at a limited part of the circumference in the pulling-zone of the tube bending, have an adverse effect, see [13].

The huge loadings, which both appear for new developed wind turbines and have to be expected for offshore wind turbines, lead to flange thicknesses above 100 mm and high-strength bolts up to M42; even bigger bolts are discussed. The fatigue-strength of such massive flanges in correlation with such bolts is part of future research activities.

Next to bolted connections also welded connections like tripod joints are topic of current research project in the fatigue sector (see Fig. 11).

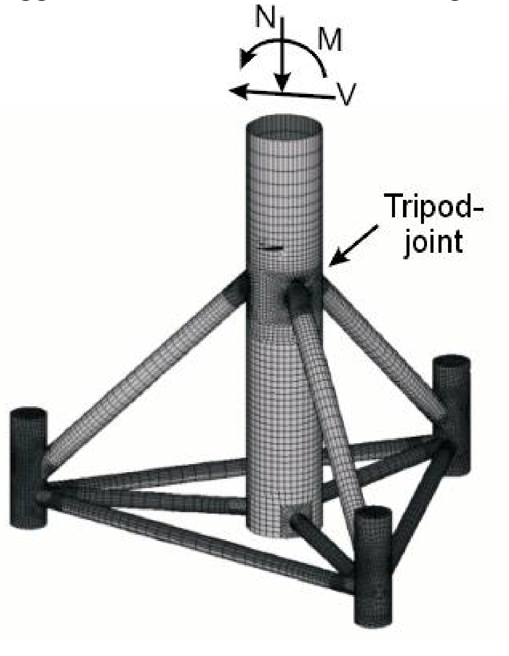


Fig. 11: FE-model of a tripod

4 Summary and Perspective

The wind energy has an important potential for the European steel industry in the upcoming years. The market has steadily grown with the demand for renewable energy sources in the last years. Even if the erection of new onshore wind energy converters is expected to decrease in Germany over the next couple of years the so-called "repowering", where older and inefficient converters are replaced with converters of current capacity, will get more and more important. Other European countries are now increasing their wind energy activities in the onshore sector. The perspective for the developing offshore wind energy is promising. While the plannings for wind energy in the German North- and Baltic Sea feature an impressive scenario for the future, other countries like Denmark, Ireland and Great Britain have already finished their first projects.

At "Horns Rev" for the support structures nearly 30,000 to of steel were used – that equals 180 to per MW of installed capacity. This demonstrates that in comparison to onshore-towers offshore support structures require more than twice the steel mass per MW. The steel substructure of the nacelle and further secondary equipment elements are not added yet.

The steel weight depends on many factors like the water depth, soil conditions, converter size and tower height. For offshore wind turbines in greater water depths higher construction weights have to be expected in relationship to the turbine capacity. This opens a great perspective to the steel industry for the upcoming years. But this perspective depends on the realisation of the still upcoming ambitious offshore plans in Europe. It will be important for steel industry companies, which want to participate in this market, to get experiences in the realisation of offshore projects quickly.

The technical challenges are manifold in this field. Some special topics, which concern the design and the dimensioning, are currently analysed in different research studies. Further themes like new fabrication technologies for the efficient production of tubular joints and the development of sufficient coastal fabrication sizes shall be mentioned here.

5 Literature

[1] DEWI [editor]: Wind Energy-Study 2002. Study available at: http://www.hamburg-messe.de/wind. (in German)

[2] DIBt [editor]: Guideline for wind energy converters – Loads and stability proof for the tower and the foundation. 1993 Berlin. (in German)

[3] DIN V ENV 61400-1: Wind Energy Converters - Part 1: Safety demands (IEC 61400-1:1994). Juli 1996. (in German)

[4] German Lloyd [editor]: Guideline for the Certification of Wind Turbines. 1999 Hamburg

[5] Johnsen, B.: Wind energy converter market 2002. Hannover: Sun Media 2002. (in German)

[6] Kaiser, K.: Stiffness- and damping matrices of wind turbines caused by wind forces and their influence on the stability behavior. Diss. TU Berlin. Progress-Report VDI set 11 Nr. 294. Düsseldorf: VDI publisher 2000. (in German)

[7] Lange, H.: Fatigue loading of tubular wind energy steel towers at inland locations. Diss. University of Essen 2002. (in German)

[8] Schaumann, P.; Kleineidam, P.: Influences on the fatigue of support structures of OWECs. Symposium Offshore-Windenergie Bau- und umwelttechnische Aspekte (GIGAWIND), 9. September 2002, Hannover (in German)

[9] Schaumann, P.; Kleineidam, P.: On the design of support structures of offshore wind energy converters. Renewable Energies 07/2001, S. 32-35. (in German)

[10] Schaumann, P.; Kleineidam, P: Support Structures and Foundation Concepts for OWECS, World Wind Energy Conference and Exhibition, Berlin, 4-8 July 2002

[11] Schaumann, P.; Kleineidam, P: Support Structures of OWECS in a Water Depth of about 30 m. Special Topic Conference, Brussels, 10-12 December 2001.

[12] Schaumann, P.; Kleineidam, P; Seidel, M.: To the FE-modelling of pulled bolt connections. Steel Construction 70 (2001), S. 73-84. (in German)

[13] Schmidt, H.; Jakubowski, A.: Fatigue safety of imperfect pre-stressed ring flange joints at tubular steel constructions under wind loading. Final report of the research project DIBt-Gesch.Z.: IV 12-5-16.104-912/99, December 2001. (in German)

[14] Seidel, M.: On the design of bolted ring flange joints of wind energy converters. Diss. University of Hannover, 2001. (in German)

[15] Schaumann, P.; Seidel, M.: Fatigue loading of bolted ring flange joints of wind energy converters. Steel Construction 71 (2002), S. 204-211. (in German)

[16] Schaumann, P.; Böker, C.; Kleineidam, P.: Development and Evaluation of Different Fatigue Design Methods for OWECs under Wave Loading. EWEC 2003 – European Wind Energy Conference, Madrid, 16-19. June 2003, 06/2003

[17] Wheeler (1970): Method for Calculating Forces Produced by Irregular Waves. Journal of Petroleum Technology, Vol. 22 (1970), S. 359-367.

Publications by the authors see: www.stahlbau.uni-hannover.de