

Project Certification of Offshore Wind Farms

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Due to the large investments involved in establishment of offshore wind farms, 3rd party verification and certification services are often required by investors and insurance companies in order to reduce their risk and protect their investments. Furthermore, the verification services may contribute positively in the project design phase minimising the cost for design changes.

Project certification of offshore wind farms will consist of different activities, however the present paper focuses on the structural design verification of offshore foundations and type approval of the wind turbine.

The design of offshore wind farms requires mastering of multiple engineering disciplines. There are several engineering challenges when locating wind turbines offshore such as waves in shallow water, breaking waves, ice loading, scour, dynamic loading due to combined waves and wind.

Based on the certification activities carried out in connection with the 'Middelgrunden Offshore Wind Farm Project', Denmark as the reference project, the paper focuses on the regulatory framework (standards, codes, design basis, recommendations) and methods applied for design and certification of offshore wind farms.

1. General

Project certification of offshore wind farms may consist of the following services:

- Type Approval of the wind turbine
- Risk Analysis (project risk, environmental risk, ship collision risk etc.)
- Structural design verification
- Manufacturing survey
- Marine verification and Warranty Survey for transport and installation of structures
- In-service inspection planning and inspection of structures

The project certification is normally carried out as a review of the design documentation submitted by the manufacturer. In addition to documentation review, independent (FE) analyses may be carried out for critical details.

Structural design verification may cover wind turbine foundation and other structures, e.g. offshore transformer station for the wind farm.

Manufacturing survey takes place at the fabrication site. The survey for welded structures is based on a review of welding procedures, welder's qualifications, NDT procedures, NDT findings etc.

Marine verification is carried out as documentation review of the designers calculations for transport and lift situations, while warranty survey is carried out at the load-out site and on board installation vessel during installation. Marine verification may e.g. be carried out based on Ref. [1].

2. Design Standards and Calculation Methods

There are currently no national standards covering design of offshore wind farms.

The applied Design Standard for offshore wind farms should include all relevant aspects related to the following areas:

- Wind Turbine Design
- Foundation Design
- Integrated design of wind turbine and foundation
- Offshore Technology
- Selection of target failure Probability, P_F
- Combined Load Cases (Wind-Waves, Wind-Ice)

All of the above areas are in principle equally important for the design of offshore wind farms.

One (new) recommendation fulfilling the above is the "Danish Recommendation for Technical Approval of Offshore Wind Turbines", June 2001, Ref. [2]. This Recommendation is an Annex to the Danish

Certification Scheme for wind turbines. The Recommendation is prepared with funding from the Danish Energy Agency.

The Danish Recommendation provides state-of-the-art guidelines for design of offshore wind turbines and foundations. It has been applied as the Basis of Design for offshore wind farms in e.g. all of the offshore wind projects in Denmark and also in several offshore wind projects in Sweden.

As an example, Ref. [1] provides useful design guidelines regarding calculation of wave loads from breaking waves in shallow waters. In shallow waters (e.g. 5-15 m water depth), the following conditions are of paramount importance:

- Finite wave heights
- Horizontal particle velocities in the crest of breaking waves are considerable higher than calculated by e.g. linear (Airy) wave theory or Stokes 5th order wave theory
- Wave crests are significantly higher than wave troughs (up till approx. 3 times the height of the trough rather than having the same magnitude as the trough)

These conditions necessitate that particular methods, comprising both effects of shallow waters (including refraction and breaking) and diffraction, are required in order to determine the wave loads. The consequence of the above is e.g. that wave loads calculated by linear (Airy) wave theory will underestimate the wave loads from breaking waves by a factor ~ 1.5-2.0.

In some areas where offshore wind turbines are sited, ice loads needs to be considered. Ref. [2] also provides design guidelines on calculation of static and dynamic ice loads, respectively considering both foundation structures with and without an ice cone. In fact combined wind and ice has been the governing load case in the design of the foundation for some of the Danish Offshore Wind Farms, ref. e.g. the 'Middelgrunden Offshore Wind Farm Project.

For combined load cases, e.g. combined wind and waves, it is in general a conservative approach to fully correlate the maximum load from the wind with the maximum load from the waves, and apply the partial safety factor for the wind on the sum of the load components. However, such an approach may in some cases turn out to be overly conservative. In Annex C ("Weighed Partial Load Factor Method") of Ref. [2] an alternative method for calculating combined loads are presented. The need for weighed safety factors arises from the computational requirement that load safety factors are applied after response calculations. The motivation for using the method presented is an optimisation of the structural design of the support structure (wind turbine tower and foundation).

The input for the method in Ref. [2] is:

- a) Simulations of the relevant (stochastic) time series for wind-, wave and ice loads
- or
- b) Calculated characteristic (deterministic) wind, wave and ice loads based on recognised standards and/or model tests which enter into the "The Simple Calculation Model"

The weighed partial load factor, f_w for e.g. the extreme load for the combined wind and waves load case can then be calculated from the following equations:

- a) Based on (2) time simulations of combined time series of wind- and waves (R_{max} = maximum load response value, p = probability of exceedance):

$$f_w = \frac{R_{max}(\text{wind+waves for } p=7.6 \times 10^{-4}/\text{year})}{R_{max}(\text{wind+waves for } p=2 \times 10^{-2}/\text{year})}$$

or

- b) Based on deterministic loads, R_{wind} and R_{wave} for $p=7.6 \times 10^{-4}/\text{year}$:

$$f_w = \frac{0.5 \times R_{wind} + ((0.5 \times R_{wind})^2 + R_{wave}^2)^{0.5}}{R_{max}(\text{wind+waves for } p=2 \times 10^{-2}/\text{year})}$$

It should be added, that the safety system in the Danish Standards is based on characteristic extreme load values corresponding to the 50 years extreme load values ($p = 2 \times 10^{-2}$). Furthermore, for the latter method b) as given above, it is assumed that the mean wind load is half of the mean of the maximum wind loads.

Further details regarding the "Weighed Partial Load Factor Method", i.e. other applications, assumptions and limitations for method, justification of the method etc., are given in Annex C of Ref. [2].

3. Certification of 'Middelgrunden Offshore Wind Farm'

The Certification of the 'Middelgrunden Offshore Wind Farm', Denmark was carried out on behalf of SEAS Distribution A.m.b.a. (Project Developer) and Bonus Energy A/S (Wind Turbine Manufacturer).



Wind Turbines:

20 x BONUS 2 MW
Active Stall
Hub Height: 64 m
Rotor Diameter: 76 m

Foundations:

Concrete gravity based foundations with cast-in steel cylinder section.

Fig. 1. Middelgrunden Offshore Wind Farm with 20 Bonus 2 MW Wind Turbines on Concrete Gravity Foundations

Fig. 1 provides some of the main data etc. for the Middelgrunden Offshore Wind Farm.

3.1 Wind Turbines

The wind turbines are certified with an A-type Approval according to the Danish Certification Scheme. Apart from the design document review and the independent load verification (Flex4 calculations), the certification of the wind turbine also included verification of the following main items:

- Load measurements
- Power performance measurements
- Noise measurements
- Static and Dynamic Blade Testing
- Special (offshore) corrosion protection system
- Special cooling systems designed for offshore conditions

3.2 Foundations

The gravity based foundation for the Middelgrunden Offshore Wind Farm is carried out as a composite concrete-steel foundation structure with a circular foundation base slab. The design of the foundation is carried out by Carl Bro A/S. The diameter of the base slab varies between 16.7 and 17.6 m, and the height of the slab varies between 1.5 m and 2.2 m at the interface between the base slab and the shaft of the foundation. Length of shaft plus the ice cone is 8.0 m for the most shallow foundation and 11.8 m and for the deepest foundation. The characteristic concrete compressive strength is 40 MPa (with a required water-cement ratio, $v/c < 0.42$) for the structural concrete and 15 MPa for the mass concrete inside the steel cylinder section. The concrete cover is minimum 55 mm including tolerances. For reinforcement, ribbed bars of steel Quality Tentor, K550TS is used. The foundation is provided with a cathodic protection design system resembling the cathodic protection

system used on typically offshore platforms in e.g. the North Sea.

The foundations are directly resting on moraine clay/sand with a soil carrying capacity of $c_u = 300$ kPa (7 foundations) or directly on limestone with $c_u = 125$ kPa (13 foundations).

In addition to the design document review and the independent load verification, the certification of the foundation also included an independent Finite Element (FE) Model Analysis of the foundation structure.



Fig. 2 FE Analysis Model of the foundations at Middelgrunden showing the deformed shape from the FE analysis calculations.

Fig. 2, which shows the deformed shape of the foundation structure calculated from the (COSMOS) FE Model, also illustrates why an independent FE Analysis was required. Applying the external bending moment at the top of the foundation steel cylinder section, slip (in a horizontal direction) between the steel cylinder and the concrete will occur in the two hatched areas shown in Fig. 2 (e.g. at the top right side of the foundation), whilst contact between concrete and steel will occur 'on the opposite sides' of the foundation structure. The calculation of these horizontal contact forces could not be carried out by hand.

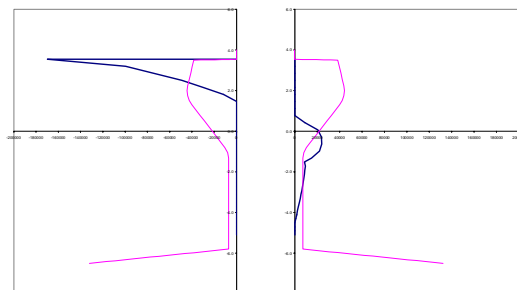


Fig.3 Distribution of the horizontal contact forces between the steel cylinder and the concrete structure.

The horizontal contact forces (see also Fig. 3) had to be calculated applying FE modelling using special contact elements between the steel cylinder section and the concrete structure. The result of the FE Analysis revealed that approx. 60 % of the external bending moment applied at the top of the foundation is resisted by these horizontal contact forces.

4. Conclusions

The applied Design Standard for offshore wind farms should include all relevant aspects related to the following areas:

- Wind Turbine Design
- Foundation Design
- Integrated design of wind turbine and foundation
- Offshore Technology
- Selection of target failure Probability, P_F
- Combined Load Cases (Wind-Waves, Wind-Ice)

All of the above areas are in principle equally important for the design of offshore wind farms.

Limitations and assumptions for the use of the Design Standard should be clearly stated.

The Design Standard should be based on a rational basis allowing for extension and continuous updating to meet the needs for an up-to-date and relevant regulatory framework basis for all of the coming different offshore wind farm projects planned for in Europe. A Design Standard with a 'fixed rules format' and e.g. with a fixed partial safety factor system only is in this context not the preferable standard.

5. References

Ref. [1]: "DNV Rules for Planning and Execution of Marine Operations", January 1996 incl. Correction Sheet No.1, September 1996.

Ref. [2]: "Danish Recommendation for Technical Approval of Offshore Wind Turbines", The Danish Energy Agency, June 2001.