Structurally optimised towers made of UHPFRC in segmental construction for offshore wind turbines

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1 Introduction

The foundation and tower structures of offshore wind turbines (OWT) that are installed to date are predominantly made of steel. One of the advantages of steel structures is their relatively low weight while having a high stiffness. However, disadvantageous are the high fabrication costs of the steel segments and the elaborate and costly corrosion protection as well as the renewal of the anticorrosive coating. For structures made of steel this is required at least once within the service life of an OWT, which is usually 20 years.

An economically promising alternative to tower structures made of steel provide externally prestressed tower structures made of ultra-high performance fibre reinforced concrete (UHPFRC) in segmental construction. In order to demonstrate the feasibility of such an innovative tower concept the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart and the Endowed Chair of Wind Energy at the University of Stuttgart partnered with Ed. Züblin AG and Lafarge for a research project that is described below.

2 Subject of the research project

2.1 Design basis und logistic concept

2.1.1 Design Basis

The Design Basis is a document in which information about the location and the characteristics of the OWT, the soil properties as well as the maritime conditions and wind conditions are detained.

As a representative site a location in the Exclusive Economic Zone (EEZ) of the North Sea with a water depth of 39.50 m LAT (lowest astronomical tide) was chosen. The characteristics of the OWT were defined on the basis of publicly available information for turbines with a rated output of 5 megawatts. The soil properties as well as the maritime and wind conditions were put together by the Central Engineering Division of Ed. Züblin AG.

In addition, the hydrological and meteorological data in the EEZ of the North Sea that were measured at the location of the North Sea Buoy II (NSB II) and the research platform FINO1 were evaluated and wave distribution diagrams, also known as Scatter-Diagrams, were derived to describe the long term behaviour of the sea state. An assessment with regards to their suitability for the chosen location of the OWT resulted in detaining the scatter diagrams for the location of the NSB II in the design basis and using them for the dynamic load calculation of the OWT.

2.1.2 STRABAG Serial System

The STRABAG Serial System is a system solution developed by the Central Engineering Division of Ed. Züblin AG that enables a production line process covering the construction, assembly, transport and erection or installation of an OWT [1]. The unique feature of the system solution is that the complete wind turbine will be constructed and assembled on land. The fully operational wind turbine is then taken by a special carrier to the operating site and installed on the previously prepared seabed.

The objective of the logistic concept based on the system solution is primarily to minimize the cost-intensive work and the associated risks at sea. Thus, the narrow time frame in which the necessary weather and sea conditions are given for executing the works at sea is optimally utilised.

The logistic concept is aligned with the structural solution for the OWT that was developed by the Central Engineering Division of Ed. Züblin AG. The structural solution consists of a gravity base foundation [2, 3] and a tubular steel tower on top of it.

2.2 Conceptual design of a tower structure made of UHPFRC in segmental construction

Taking into account the various requirements for a tower structure for offshore wind turbines an alternative to a tabular steel tower was developed within this research project. This is a centrically prestressed tower structure made of UHPFRC in segmental construction.

UHPFRC is an ideal material for the use in structures of OWT due to its outstanding material properties. Regarding its mechanical properties UHPFRC has a higher compressive strength and higher fatigue strength than normal or high-strength concrete, which allows for slimmer and lighter structures. The reduction of the self-weight is directly linked to savings of raw material and energy, which is increasingly gaining in importance in times when resources are becoming scarcer. In addition, UHPFRC is a material with a high durability due to its high packing density. The repair and maintenance costs, particularly with regards to corrosion protection, are significantly lower for structures made of UHPFRC than for structures

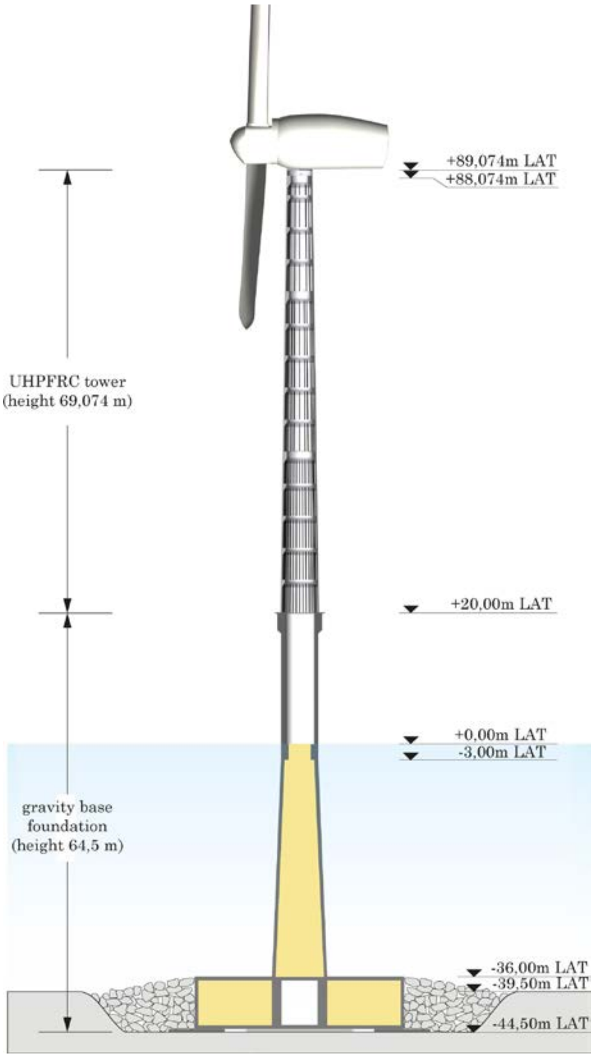


Figure 1: Section of the structure consisting of a gravity base foundation and an UHPFRC tower

made of steel. This implies lower life cycle costs and therefore a higher profitability of the wind turbine. The segmental construction method, and thus the serial prefabrication of tower segments at a plant, ensures on the one hand a consistent high material quality and dimensional accuracy of the tower segments and reduces on the other hand the production costs through the efficient use of materials and an aligned work process.

The UHPFRC tower has a height of 69.074 m (Figure 1). The tower is conical over its height. The external diameter at the base of the tower is 6.00 m and at the top of the tower 4.006 m. The tower is divided into 14 segments, of which the lower 13 segments have a height of 5.00 m and the top segment has a height of 4.074 m. The topmost segment is equipped with a steel adapter that is required for the transition from the UHPFRC tower to the azimuth bearing of the nacelle.

The UHPFRC tower is centrically prestressed through external tendons, which run outside the cross section on the inside of the tower. Thus, the wall thickness of the individual tower segments can be reduced to the minimum. External tendons can also be inspected, re-tensioned and replaced. The tendons are staggered over the height of the tower according to the bending moment. At the top of each segment is a console on which the external tendons can be either anchored or by which they are horizontally held in position. When the tower structure is in its deflected shape the tendon profile is polygonal and there are no second order effects due to eccentricities of the tendons with reference to the system axis.

The joining technology not only has to ensure the load transfer between the tower segments, but also to facilitate an easy assembly and disassembly of the tower structure. Both of these requirements are achieved by tensioning the tower segments together with dry joints between the tower segments.

2.3 Experimental investigation of the material behaviour of UHPFRC

Precise knowledge of the material behaviour is the basis of each design. Within this research project an UHPFRC developed by Lafarge under the label Ductal ® was investigated in terms of its mechanical properties. The UHPFRC contained steel fibres (2.0 Vol.-%) of the type Redaelli (l_f / d_f = 14 mm / 0,185 mm) and has been subjected to heat treatment.

The following material parameters were determined amongst others:

- compressive strength of 18 cylinders with a diameter of Ø = 100 mm and a height of h = 200 mm: f_c = - 211.3 MPa with a coefficient of variation of v = 5.70 %;
- Young's modulus under compressive loading of 9 cylinders with a diameter of Ø = 100 mm and a height of h = 200 mm: E_c = 59364 MPa with v = 1.14 %;
- flexural strength of 9 prisms without a notch and a cross section with a width of b = 75 mm and height of h = 75 mm: f_{ctfl} = 39.57 MPa with v = 8.76 %;
- flexural strength and crack width of 6 prisms with a notch and a cross section with a width of b = 75 mm and a height of h = 75 mm minus a notch depth of h_k = 25 mm: f_{ctfl} = 29.38 MPa with v = 6.08 % and $w_r(f_{ctfl})$ = 0.55 mm with v = 13.59 %;
- axial tensile strength of 9 test specimens without a notch and a cross section with a width of b = 75 mm and a height of h = 75 mm: f_{ct} = 14.54 MPa with v = 4.19 %;

- axial tensile strength and crack width of 9 test specimens with a notch and a cross section with a width of b = 50 and a height of h = 50 mm: f_{ct} = 16.42 MPa with v = 9.36 % and $w_r(f_{ct})$ = 0.306 mm with v = 34.77 %.

In the wake of the tensile tests on the test specimens with a notch the tensile strength for a one-dimensional fibre orientation (1D) was determined by measuring the fibre orientation in the area of the notch. The measuring device used for this purpose and the mathematical description of the non-linear correlation between the fibre orientation and the 1D tensile strength are shown in [4]. The 1D tensile strength amounted to $f_{ct,1D}$ = 25.96 MPa. The results of the experimental investigation on the material behaviour formed the basis for the derivation of the characteristic values (5 % fractile). The characteristic cylinder compressive strength amounted to f_{ck} = - 183.8 MPa, the characteristic 1D tensile strength amounted to $f_{ctk,1D}$ = 22.74 MPa.

2.4 Preliminary design of the tower structure made of UHPFRC in segmental construction

An Eigen frequency analysis of the load-bearing structure consisting of a gravity base foundation and an UHPFRC tower with a wall thickness of t = 200 mm showed that the distance between the Eigen frequency of the structure and the excitation frequencies is sufficient and that it can be achieved a "soft-stiff" design with reference to the resonance diagram, also known as Campbell-Diagram.

Starting with an UHPFRC tower with a wall thickness of t = 200 mm several variants of the tower were examined with a view to demonstrate in principle the feasibility of the UHPFRC tower in the ultimate and serviceability limit state as well as to reduce the material usage by decreasing the wall thickness of the tower segments.

The loading on the entire system consisting of self-weight, the environmental conditions with respect to wind and waves as well as the operating conditions were determined by a dynamic load calculation of the entire system with the simulation software Flex 5. As the prestressing forces of the UHPFRC tower could not be taken into account by the software, the loading due to the prestressing forces had to be determined separately as well as the loading due to temperature and imperfection.

A non-linear calculation of the internal forces and moments was necessary for the ultimate and serviceability limit state design. For the non-linear calculation the moment-curvature relationship is of foremost importance. The curvature depends amongst others on the degree of prestress, i.e. if in the ultimate limit state the joints between the segments are closed or whether to allow them to partially open.

A preliminary design of the load-bearing structure revealed that the degree of prestress is crucial for the optimization of the wall thickness of the tower segments. The reason for this is that the fatigue behaviour of concrete under compression shows a significant dependence on the mean stress, i.e. with increasing mean stress decreases the number of load cycles at failure for the same amplitude. Therefore a lower degree of prestress leads to a more efficient tower structure. This implies, however, that the load transfer in the joints can be ensured through an appropriate joint geometry, in particular the load transfer in partially open joints - even under torsion - and the transmission of the loads into the subsequent segments. For this reason, the load-bearing behaviour of dry joints under static and cyclic loading was investigated within this research project.

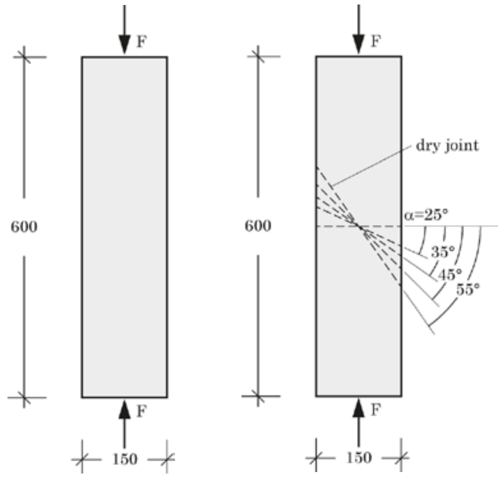
2.5 Experimental investigation of joints

2.5.1 Experimental investigation of the load-bearing behaviour of dry joints under static loading

For the determination of the load-bearing behaviour of dry joints under static loading compression tests with and without joints were carried out according to Figure 2.

In total 53 test specimens were tested:

- compression test on 5 test specimens without joint (reference prisms);
- compression test on:
  - 9 test specimens with a very smooth joint (3 test specimens at a time with an inclination of the joint α of 0°, 25° and 35°);
  - 9 test specimens with a blasted joint (3 test specimens at a time with an inclination of the joint α of 0°, 25° and 35°);
  - 15 test specimens with a rough joint (3 test specimens at a time with an inclination of the joint α of 0°, 25°, 35°, 45° and 55°);
  - 15 test specimens with an indented joint (3 test specimens at a time with an inclination of the joint α of 0°, 25°, 35°, 45° and 55°).



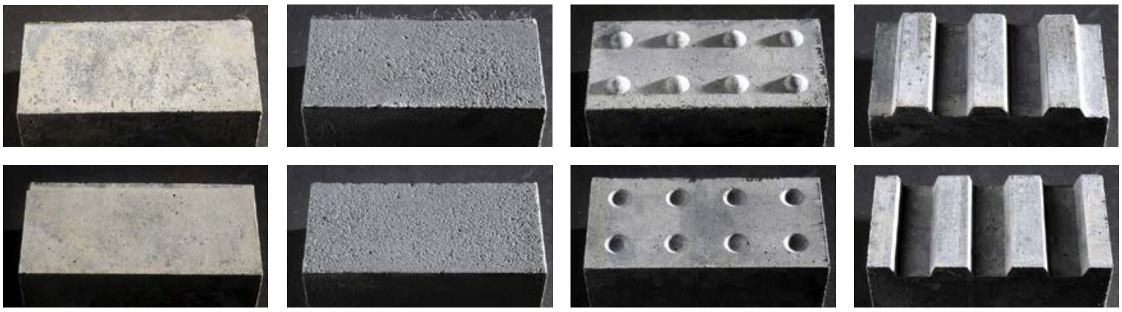
a) Compression test without joint

b) Compression test with joint

Figure 2: Test specimens for the determination of the load-bearing behavior of dry joints under static loading (dimensions in mm)

The compression tests were conducted with the aim to determine the relationship between the shear and normal stress τ_j and σ_j in the joint in order to assess the influence of the joint geometry (Figure 3) on the load-bearing behaviour of dry joints.

The results of the compression tests can be depicted in a diagram that emerged from theoretical considerations of [5]. Hereby the point is plotted in the diagram that indicates the shear and normal stress τ_j and σ_j in the joint at failure of the test specimen (Figure 4).



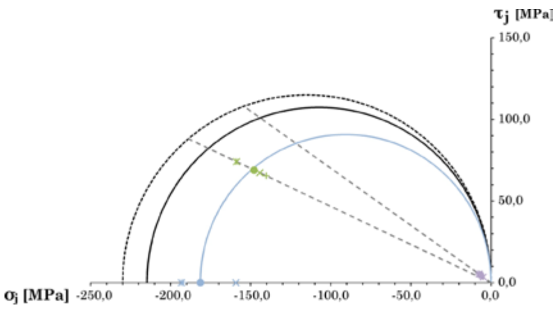
a) very smooth

b) blasted

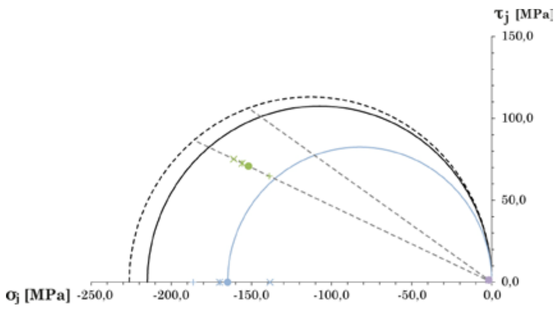
c) rough

d) indented

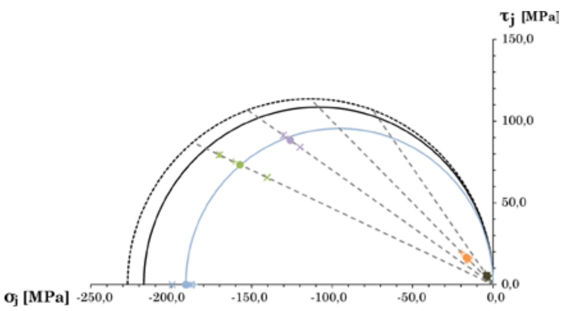
Figure 3: Joint geometry of the upper (depicted in the upper picture) and lower part of the test specimen (depicted in the lower picture)



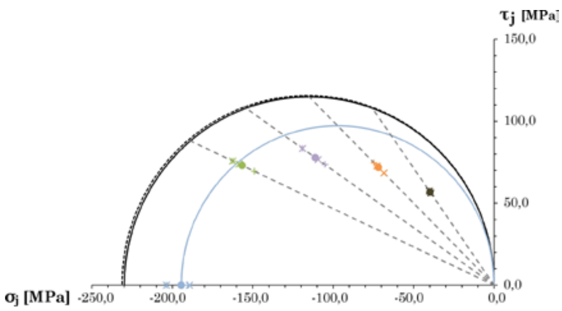
a) Test specimens with a very smooth joint



b) Test specimens with a blasted joint



c) Test specimens with a rough joint



d) Test specimens with an indented surface

Figure 4: Diagrams depicting the results of the compression tests on test specimens with joints

2.5.2 Experimental investigation of the load-bearing behaviour of dry joints under cyclic loading

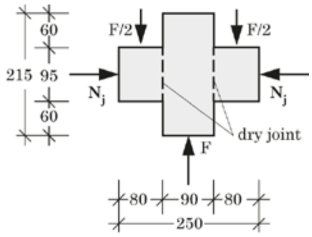


Figure 5: Test specimen for the determination of the load-bearing behaviour of dry joints under cyclic loading (dimensions in mm)

Based on the experimental investigation of the load-bearing behaviour of dry joints under static loading push-out tests with test specimens according to Figure 5 were conducted for the determination of the load-bearing behaviour of dry joints under cyclic loading.

The push-out tests were conducted first under static loading to derive the absolute values of the upper and lower loads for the push-out tests under cyclic loading.

In total 78 test specimens were tested:

- push-out tests under static loading on:
  - 15 test specimens with a very smooth joint (5 test specimens at a time with a stress normal to the joint of 6 MPa, 40 MPa and 90 MPa);
  - 22 test specimens with an indented joint (5 test specimens at a time with a stress normal to the joint of 6 MPa, 40 MPa and 90 MPa and 7 test specimens with a stress normal to the joint of 0 MPa);
- push-out tests under cyclic loading on:
  - 12 test specimens with a very smooth joint (1 or 2 test specimens at a time with a stress normal to the joint of 6 MPa, 40 MPa or 90 MPa und an upper load level of 0.80, 0.85 or 0.90);
  - 29 test specimens with an indented joint (1 or 2 test specimens at a time with a stress normal to the joint of 6 MPa, 40 MPa or 90 MPa and an upper load level of 0.80, 0.85 or 0.90 as well as 3 or 6 test specimens at a time with a stress normal to the joint of 0 MPa and an upper load level of 0.60, 0.65, 0.70, 0.75 or 0.80).

The push-out tests under cyclic loading were conducted with the aim to investigate the fatigue behaviour of joints as a function of the stress normal to the joint. The number of load cycles at failure and the deformation parallel to the joint as a result of the cyclic loading were recorded. Test specimens that did not fail under cyclic loading were subsequently tested under static loading to determine the residual load-bearing behaviour.

In terms of the number of load cycles at failure it was found that with a stress normal to the joint of 6 MPa, 40 MPa and 90 MPa and the test specimens subjected to an upper load level of 0.80, 0.85 and 0.90 and a lower load level of 0.05 at least one test specimen did not fail. This applied to both test specimens with a very smooth joint and test specimens with an indented joint. Test specimens with an indented joint and a stress normal to the joint of 0 MPa failed prematurely at upper load levels of 0.65, 0.70, 0.75, 0.80 and a lower load level of 0.05. Only under an upper load level of 0.60 and a lower load level of 0.05 at least one test specimen did not fail.

During the cyclic loading the deformation parallel to the joint did not or only slightly increase. This observation applied to both test specimens with a very smooth joint and test specimens with an indented joint.

The determination of the residual load-bearing behaviour revealed that the shear stress τ_j after previous cyclic loading was significantly higher than the average shear stress τ_j that resulted from push-out tests under static loading without previous cyclic loading. This was the case for both test specimens with a very smooth joint and test specimens with an indented joint with a stress normal to the joint of 6 MPa, 40 and 90 MPa and the test specimens subjected to an upper load level of 0.80 0.85 and 0.90 and a lower load level of 0.05. Test specimens with an indented joint and with a stress normal to the joint of 0 MPa and the test specimens subjected to an upper load level of 0.60 and a lower load level of 0.05 exhibited after previous cyclic loading a slightly lower shear stress τ_j than the average shear stress τ_j that resulted from push-out tests under static loading without previous cyclic loading.

3 Conclusion

The research project made an important contribution to the development of tower structures for OWT made of UHPFRC in segmental construction. It has been shown that the use of the high-performance material UHPFRC in combination with the segmental construction method represents a promising alternative to tubular steel towers.

To go beyond the stage of a feasibility study and to promote the construction of a first prototype, the key issues investigated within this research project have to be discussed in even greater depth and further key issues beyond the realm of this research project have to be clarified. This concerns the development of a standard for the high-performance material UHPFRC as well as design rules for tower structures made of UHPFRC in segmental construction. With regards to this, design rules for dry joints will be developed based on both the experimental investigation carried out within this research project on the load-bearing behaviour of dry joints under static and cyclic loading and on theoretical and empirical approaches for dry joints. Fabrication issues are also to be clarified. One issue relates to the achievable accuracies with regards to the joints in practical terms and the impact of inaccuracies or other imperfections on the load transfer in the joint. Another issue is to select a suitable casting or pouring method so that in view of the loading of the tower segments an optimal distribution and orientation of the fibres can be achieved.

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Figures