

## **CONCEPTUAL DESIGN OF AN UHPFRC TOWER STRUCTURE IN SEGMENTAL CONSTRUCTION FOR OFFSHORE WIND TURBINES**

**Werner Sobek (1, 2), Markus Plank (1), Björn Frettlöhr (3), Jochen Röhm (4) and Dominique Corvez (5)**

- (1) Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, Germany
- (2) Illinois Institute of Technology (IIT), Chicago, USA
- (3) EnBW Erneuerbare Energien GmbH, Hamburg, Germany
- (4) Zentrale Technik, Ed. Züblin AG, Stuttgart, Germany
- (5) Lafarge, Paris, France

### **Abstract**

Apart from a few limited exceptions the vast majority of offshore wind turbines consist of substructures and towers made of steel. Some innovative concepts use gravity based hybrid constructions. An economically and ecologically promising alternative could be the substitution of the steel tower by a centrally prestressed tower that combines the use of ultra-high performance fibre reinforced concrete (UHPFRC) with the segmental construction method. In this paper the concept of the UHPFRC tower structure is presented. Within the limits of the conceptual design an Eigen frequency analysis was conducted. The results of the analysis were evaluated with respect to the Campbell-Diagram and point to the feasibility of this innovative concept.

### **Résumé**

Mis à part un nombre limité d'exceptions, la majorité des éoliennes offshore, sont réalisées exclusivement en acier. Seuls quelques concepts innovants utilisent des solutions mixtes acier béton pour les fondations gravitaires. Une solution prometteuse tant sur le plan économique que celui du développement durable pourrait être de combiner l'utilisation de BFUP avec des voussoirs précontraints pour l'édification du mât. Dans cet article, le concept d'un mât BFUP est présenté. Dans les limites associées au dimensionnement préliminaire de la tour, une analyse des modes propres a été réalisée. Les résultats de celle-ci ont été évalués selon les critères associés au diagramme de Campbell et permettent d'illustrer la faisabilité de ce concept innovant au regard de cette contrainte.

## **1. INTRODUCTION**

One of the outcomes of the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 was the Agenda 21. The Agenda 21 is a global programme of action that requests the signatory states to voluntarily develop and implement a sustainability strategy. Amongst many other nations the German Federal Government complied with the request and laid out its path for a sustainable development by publishing the National Sustainable Development Strategy [1] in 2002. One of the key aspects described herein is a sustainable energy policy which aims at increasing energy efficiency and expanding renewable energies. In particular the expansion of offshore wind energy in German waters to up to 25000 MW of installed capacity by 2030 is set out as an ambitious target.

According to a recent survey [2] by the German Wind Energy Institute (DEWI), only 76 wind turbines with a total capacity of 320 megawatts were installed in the German Exclusive Economic Zone in the North Sea and Baltic Sea by the end of 2012. Due to the modest progress the German Federal Government set up funding programmes to accelerate the expansion of offshore wind energy. Among these programmes are research initiatives to advance wind turbines (i.e. blades, nacelle, tower and substructure) so that they meet the technical and ecological challenges offshore and to facilitate the connection to the national grid.

Apart from a few limited exceptions the vast majority of offshore wind turbines consist of substructures and towers made of steel. Some innovative concepts use gravity based hybrid constructions.

An economically and ecologically promising alternative could be the substitution of the steel tower by a centrally prestressed tower that combines the use of ultra-high performance fibre reinforced concrete (UHPFRC) with the segmental construction method.

The Institute for Lightweight Structures and Conceptual Design (ILEK) and the Endowed Chair for Wind Energy (SWE) at the University of Stuttgart partnered with Lafarge and *Zentrale Technik* of Ed. Züblin AG for a research project [3] to investigate the feasibility of such an innovative tower concept.

## **2. CONSTRAINTS OF THE RESEARCH PROJECT**

### **2.1 Design Basis**

The Design Basis is a document that contains amongst others the site-specific conditions for an offshore wind farm. The meteorological, oceanographic and geological conditions were provided by *Zentrale Technik* of Ed. Züblin AG.

Based on where wind farms are planned in the German Exclusive Economic Zone in the North Sea a representative site with a water depth of 39.50 m (lowest astronomical tide = LAT) was chosen.

### **2.2 STRABAG Serial System**

The STRABAG Serial System is a solution that enables a production line process covering construction, assembly, transport and installation of offshore wind turbines [4]. The unique feature is the complete assembly of the entire wind turbine onshore in a terminal with an industrial plant and access to a pier (Figure 1, left). From there the fully operational wind turbine is taken by a special carrier to the operating site and installed on the previously prepared seabed (Figure 2).

The structure of the offshore wind turbine is built up of a gravity base foundation and a steel tower. The gravity base foundation consists of a prestressed concrete shaft that sits on the crossing point of two orthogonal intersecting prestressed box girders (Figure 1, right).

At the end of the box girders are base plates through which the loads are transferred into the soil. Further information on the dimensions, design philosophy [5], analysis [6], full-scale model tests [7] and fatigue behaviour [8, 9] of the gravity base foundation can be found in the respective references.

The prestressed concrete shaft of the gravity base foundation and the steel tower intersect 20.00 m above LAT. The height of the steel tower is 69.07 m, the outer diameter at the top of the steel tower is 4.00 m and at the bottom 6.00 m.



Figure 1: STRABAG Terminal in Cuxhaven (left) and full-scale model of STRABAG Gravity Base Foundation (right) [4]



Figure 2: STRABAG Carrier (left) and STRABAG Gravity Base Foundation with steel tower installed at operating site (right) [5]

### 3. UHPFRC TOWER STRUCTURE

#### 3.1 Concept

Starting point for the conceptual design of the UHPFRC tower structure is the aforementioned STRABAG Serial System where the steel tower is replaced by an UHPFRC tower with the same dimensions.

The application of UHPFRC in structures entails in general the application of precast elements. The serial fabrication of precast elements in an industrial plant ensures on the one hand a consistently high quality of the material and on the other hand a reduction of manufacturing costs through an efficient workflow. The required dimensional accuracy of the precast elements can be achieved either by using high precision formwork made of steel or by match casting.

Within the limits of the conceptual design the UHPFRC tower structure was divided into 14 precast elements or segments. 13 of them have a height of 5.00 m and the topmost has a height of 4.07 m. The segments are stacked on top of each other and then the tower structure is centrally prestressed. The external tendons, i.e. the tendons are outside the cross section in the inside of the segments, allow for the wall thickness of the segments to be minimised according to the occurring stresses and there is no requirement for a minimum wall thickness as for internal tendons. External tendons can also be inspected, re-tensioned and replaced. 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 (Figure 3). When the tower structure is in its deflected shape then the tendon profile is polygonal and there are no second order effects due to eccentricities of the tendons with reference to the system axis.

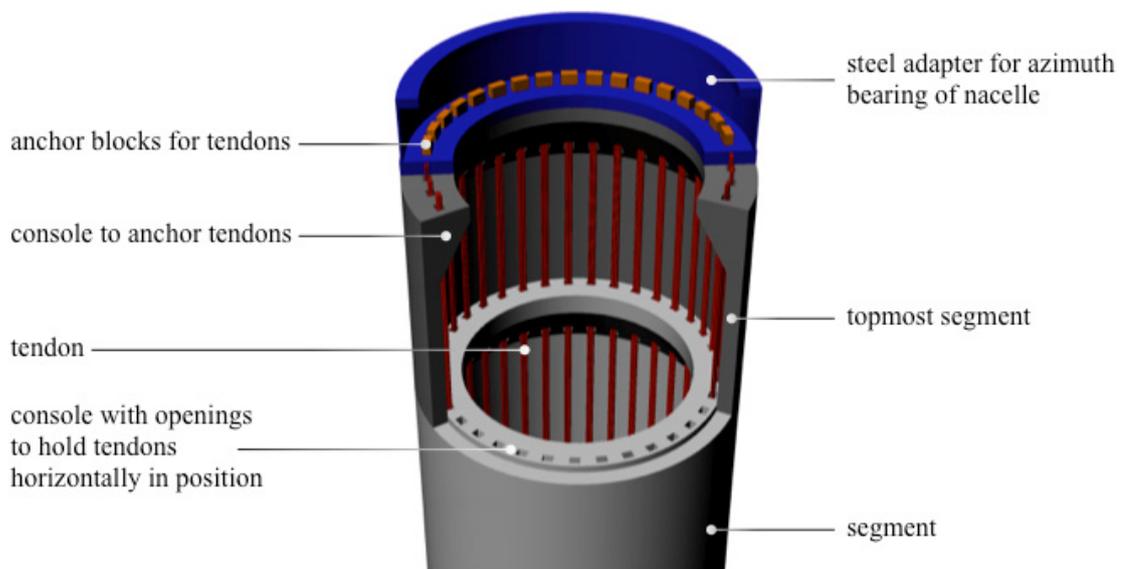


Figure 3: Anchorage of tendons at the top of the UHPFRC tower structure

The high degree of prefabrication of segments together with the segmental construction method enables a rapid progress with regards to the assembly of the wind turbine and a relatively easy disassembly of the tower structure simply by loosening the prestressing forces.

### **3.2 UHPFRC vs. normal or high strength concrete and steel**

Its unique mechanical properties and its high durability make UHPFRC an ideal material for the application in the tower structure of offshore wind turbines.

Regarding its mechanical properties UHPFRC has a higher compressive strength and a higher fatigue resistance [10] than normal or high strength concrete allowing for the execution of a leaner and lighter tower structure. The Young's modulus of UHPFRC is also higher than of normal or high strength concrete resulting in a stiffer structure for the same inertia.

Furthermore, UHPFRC is a very durable material. Due to its high packing density its resistance to climatic and chemical effects is high. As a result less cover is necessary in comparison to normal or high strength concrete. In comparison to steel structures no costly provisions are necessary to ensure adequate protection against corrosion. Steel structures require an anticorrosive coating which has to be renewed at least once within a service life of 20 years in an offshore environment. By contrast an UHPFRC tower structure shows significantly lower maintenance and repair requirements which consequently results in lower life cycle costs.

In view of the planned offshore wind farms worldwide it seems conceivable that limits in terms of the availability of steel and the capacity for the fabrication of substructures and towers made of steel will be reached. As a result steel prices and delivery times might rise and add to the advantage of using UHPFRC.

### **3.3 Mechanical properties of UHPFRC**

The UHPFRC used in the research project was Ductal® FM Grey, formulation 2GM2.0, from Lafarge. The steel fibres had a length of 14 mm and a diameter of 0.185 mm and were added at a ratio of 2.0 % by volume.

Experimental tests were conducted to characterise the mechanical properties of Ductal® FM including the Young's modulus. The test specimens used to determine the Young's modulus had a height of 200 mm and a diameter of 100 mm. They were heat-treated for at least 48 hours at a temperature of approximately 90 °C. The tests were conducted in accordance to [11]. In total nine specimens were tested and the mean value for the Young's modulus was 59364 MPa with a standard deviation of 679 MPa and a coefficient of variation of 1.14 %.

It should be noted that the extremely low coefficient of variation is very beneficial with regards to an accurate determination of the Eigen frequency of the structure.

## **4. DYNAMIC INVESTIGATION**

### **4.1 Multi-degree of freedom system**

The Eigen frequency analysis of the gravity base foundation and the UHPFRC tower was carried out with a two-dimensional multi degree of freedom system (MDFS). The principle of the MDFS for a "lumped mass" approach is shown in Figure 4.

The spring stiffness of the support is based on the dynamic soil properties and the stiffness of the box girders. The centre of gravity of the rotor and the nacelle has a horizontal eccentricity with reference to the vertical axis of the tower.

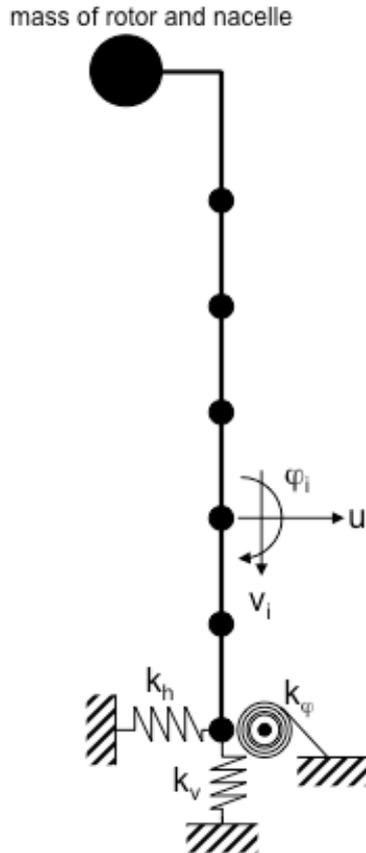


Figure 4: Principle of MDFS

The Eigen frequencies of the MDFS are a solution of the Eigen value problem:

$$\det (\mathbf{K} - \omega_i^2 \mathbf{M}) = 0 \quad (1)$$

with  $\mathbf{K}$  total stiffness matrix of the MDFS  
 $\mathbf{M}$  total mass matrix of the MDFS  
 $\omega_i$  Eigen angular frequency  $i$  of MDFS

With regards to the calculation of the Eigen frequencies it should be noted that a geometric nonlinear stiffness matrix was used and therefore normal forces were considered. In the mass matrix the mass of the rotor, the nacelle and the tower as well as the hydrodynamic mass of the surrounding seawater was taken into account. For reasons of simplification the effect of the structural and aerodynamic damping on the Eigen frequencies was not considered.

#### 4.2 Parameter study

A study was conducted to judge the impact of various parameters on the Eigen frequencies of the structure. The parameters and their variation are summarized in Table 1.

Table 1: Parameters of Eigen frequency analysis

Component of support structure	Parameter	Variation
Spring stiffness of support	Vertical and horizontal bedding modulus	$k_{sv}$ and $k_{sh}$ as stated in the Design Basis with a scatter of $-50%$ , $+100%$ and $+500%$
	Loading direction with respect to the intersecting box girders	parallel or diagonal
Shaft of gravity base foundation	Young's modulus (for concrete grade C80/95 according to [12])	$E_{cm} = 42300 \text{ MPa}$ with a scatter of $\pm 10\%$
	Wall thickness	600 mm
UHPFRC tower	Young's modulus	$E_{cm} = 59364 \text{ MPa}$ with a scatter of $\pm 10\%$
	Wall thickness	100 mm or 200 mm
Steel tower (reference tower)	Young's modulus	$E_s = 210000 \text{ MPa}$

### 4.3 Campbell-Diagram

The purpose of the Campbell-Diagram is to visualize the relation between the first Eigen frequency  $f_1$  of the structure and the excitation frequencies of the rotor. In the diagram the rotor frequency  $f_R$  (1P excitation) and the blade passing frequency  $f_B$  (3P excitation for a three-bladed wind turbine) are plotted against the rotational speed of the rotor with a scatter of  $\pm 10\%$ . The vertical lines indicate the range in which the rotor of the wind turbine operates. Thus, three design ranges can be classified with respect to the dynamic behaviour of a wind turbine [13]:

- “soft-soft” design:  $f_1 < f_R$
- “soft-stiff” design:  $f_B < f_1 < f_B$
- “stiff-stiff” design:  $f_1 > f_B$

The first Eigen frequency of the reference structure with a gravity base foundation and a steel tower is between 0.369 Hz and 0.395 Hz.

Replacing the steel tower by an UHPFRC tower with a wall thickness of 200 mm yields a first Eigen frequency between 0.357 Hz and 0.397 Hz (Figure 5). Replacing the steel tower by an UHPFRC tower with a wall thickness of 100 mm between yields a slightly lower first Eigen frequency between 0.316 Hz and 0.351 Hz (Figure 6). The scatter of the first Eigen frequency is in both cases in the “soft-stiff” design range and crosses only in the lower operating range of the rotor the blade passing frequency (3P). However, modern wind turbines are equipped with a control system that can skip the excitation frequency.

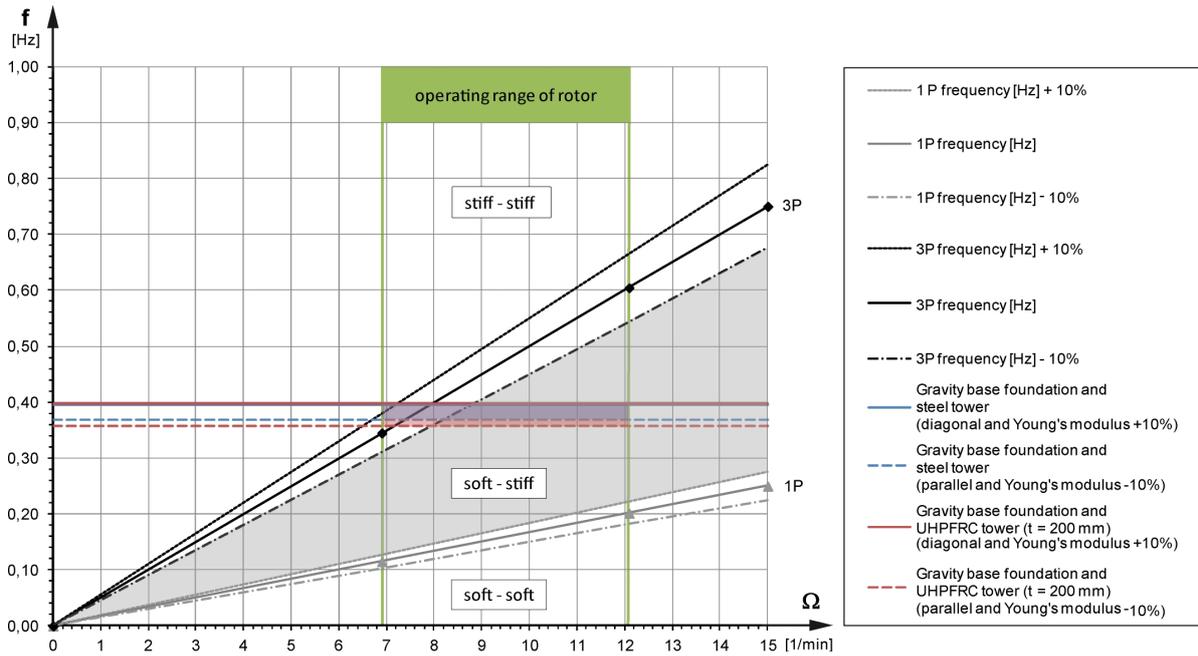


Figure 5: Campbell-Diagram for a structure consisting of a gravity base foundation and an UHPFRC tower with a wall thickness of 200 mm

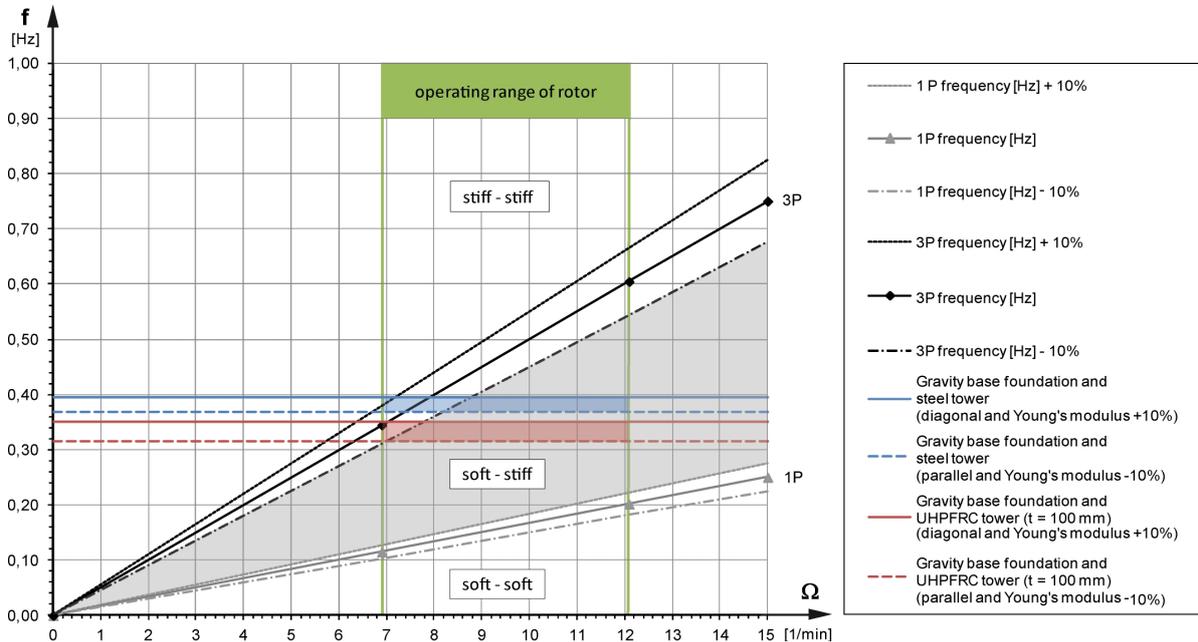


Figure 6: Campbell-Diagram for a structure consisting of a gravity base foundation and an UHPFRC tower with a wall thickness of 100 mm

## **5. FURTHER INVESTIGATIONS**

Besides the characterisation of material properties of UHPFRC and a dynamic investigation of the structure further investigations were carried out within the research project.

For the determination of the loads on the structure the software FLEX 5 was used. With this software a time domain simulation of the complete system (rotor, nacelle, tower and substructure) was performed that considered the effects due to aerodynamics, hydrodynamics and structural dynamics as well as the control system of the wind turbine. For this purpose wind and wave data recorded by the research platform FINO 1 and representative for the chosen site in the North Sea were evaluated.

A first preliminary design of the UHPFRC tower structure has shown that the degree of prestressing has a major impact on the optimisation of the wall thickness of the segments. The reason for this is that the fatigue behaviour of concrete under compressive stress is dependent on the mean stress, i.e. for the same amplitude a higher mean stress results in a smaller number of load cycles until failure. Therefore a more slender structure is achievable through lowering the degree of prestressing by allowing the joints between the segments to open in the ultimate limit state.

An experimental programme was initiated to quantify the load-bearing and deformation behaviour of dry joints under static and dynamic loads in order to inform the detailed design of the UHPFRC tower structure.

## **6. CONCLUSIONS**

The novelty of the concept presented arises from the highly advantageous combination of UHPFRC with the segmental construction method for a centrally prestressed tower structure for offshore wind turbines.

The advantages of the application of UHPFRC and the segmental construction method were highlighted together with the prestressing concept for the UHPFRC tower structure.

Within the limits of the conceptual design a parameter study regarding the first Eigen frequency of a structure consisting of a gravity base foundation and an UHPFRC tower was carried out and the result was illustrated in a Campbell-Diagram. The scatter of the first Eigen frequency lies in the “soft-stiff” design range which points to the feasibility of this innovative concept, as the dynamic behaviour is one of the governing design criterions for structures of wind turbines.

In consideration of the promising outcome of the dynamic investigation it is envisaged to not only replace the steel tower but also the gravity base foundation by an UHPFRC solution in order to deploy the full potential of UHPFRC.

## **ACKNOWLEDGEMENTS**

The findings presented emanate from a research project supported by the Federal Institute for Research on Building, Urban Affairs and Spatial Development in Germany through its *Zukunft Bau* research initiative. The support is gratefully acknowledged.

## **REFERENCES**

- [1] Bundesregierung, 'Perspektiven für Deutschland – Unsere Strategie für eine nachhaltige Entwicklung', URL: [http://www.bundesregierung.de/Content/DE/\\_Anlagen/Nachhaltigkeit-](http://www.bundesregierung.de/Content/DE/_Anlagen/Nachhaltigkeit-)

- wiederhergestellt/perspektiven-fuer-deutschland-langfassung.pdf?\_\_blob=publicationFile&v=2, accessed on 25th February 2013.
- [2] URL: <http://www.dewi.de/dewi/index.php?id=47&L=0>, accessed on 25<sup>th</sup> February 2013.
- [3] Frettlöhr, B., Plank, M., Quappen, J. H., Sobek, W., 'Strukturoptimierte Türme für Offshore-Windenergieanlagen aus UHFFB in Segmentbauweise', interim report for research project SF-10.08.18-7-09.25 / II2-F20-09-43 of *Zukunft Bau* research initiative (Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, 2011).
- [4] URL: <http://www.strabag-offshore.com/en/projects/strabag-serial-system.html>, accessed on 25<sup>th</sup> February 2013.
- [5] Hartwig, U. and Mayer, T., 'Entwurfsaspekte bei Gründungen für Offshore-Windenergieanlagen', *Bautechnik* **89** (3) (2012) 153-161.
- [6] Safinus, S., Sedlacek, G. and Hartwig, U., 'Analysis of Gravity Base Foundation for Offshore Wind Turbine under Cyclic Loads', in 'The Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference', Proceedings of an International Conference, Maui, June, 2011 (International Society of Offshore and Polar Engineers, Cupertino, 2011) 299-305.
- [7] Hartwig, U., Bierer, T. and Sommer, J., 'Full-scale Model Tests on a Gravity Base Foundation for Offshore Wind Turbines', in 'The Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference', Proceedings of an International Conference, Maui, June, 2011 (International Society of Offshore and Polar Engineers, Cupertino, 2011) 306-313.
- [8] Urban, S., Strauss, A., Wagner, R., Reiterer, M. and Dehlinger, Ch., 'Experimentelle Untersuchung von ermüdungsbeanspruchten Betonstrukturen zur Feststellung des realen Schädigungsgrades – Planung der Ermüdungsversuche am Strabag-Testfundament in Cuxhaven', *Beton- und Stahlbetonbau* **107** (7) (2012) 463-475.
- [9] Urban, S., Strauss, A., Macho, W., Bergmeister, K., Dehlinger, Ch. and Reiterer, M., 'Zyklisch belastete Betonstrukturen - Robustheits- und Redundanzbetrachtungen zur Optimierung der Restnutzungsdauer', *Bautechnik* **89** (11) (2012) 737-753.
- [10] Wefer, M., 'Materialverhalten und Bemessungswerte von ultrahochfestem Beton unter einaxialer Ermüdungsbeanspruchung', Berichte aus dem Institut für Baustoffe, Heft 7 (Institut für Baustoffe, Leibniz Universität Hannover, 2010).
- [11] DIN 1048-5, 'Testing methods for concrete; hardened concrete, specially prepared specimens', June 1991 (Beuth Verlag GmbH, Berlin, 1991).
- [12] DIN 1045-1, 'Concrete, reinforced and prestressed concrete structures-Part 1: Design and construction', August 2008 (Beuth Verlag GmbH, Berlin, 2008).
- [13] Kühn, M., 'Dynamics and Design Optimisation of Offshore Wind Energy Conversion Systems', Report 2001.002, 2nd Edn (DUWIND Delft University Wind Energy Research Institute, Delft, 2003).