ULTRA HIGH PERFORMANCE CONCRETE BARS IN FRAMEWORK FOR HYBRID²-TOWERS

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ABSTRACT

The hybrid²-tower, which is developed in a research project funded by a German organization, is a very economical solution to reach a large tower height for onshore wind turbines. In the lower part of the tower, the construction is build out of a reinforced concrete framework with corner elements and strut elements. In the upper part, a tubular steel tower is placed on the lower concrete pedestal, on which the power generating equipment is installed. In relation to material and cost savings, many advantages occur by using Ultra-High Performance Concrete (UHPC) for the strut elements of the lower part instead of normal concrete.
The conventional mixing of UHPC, made with a lot of fine concrete admixtures, such as silica fume and silica flour, needs high-performance pan mixer. Because of that, the practical application is severely restricted. In laboratory experiments at the Technische Hochschule Mittelhessen the application of UHPC for practice was examined with usual coarse aggregate and a special cement compound in different conventional pan mixers.
As a result, UHPC is applicable for practice and for concrete beams of hybrid²-towers. The higher compressive strength of UHPC can be used for cross-sectional reduction, which leads to material saving. The costs for transport and assembly can be reduced due to the low weight of the tower.

Keywords: Research Project, Hybrid-Towers, Onshore Wind Turbines, UHPC, Precast Concrete Elements, Prestressed Concrete Elements

INTRODUCTION

Currently, the development of wind turbines is in a strong demand in Germany. For this reason, the Technische Hochschule Mittelhessen developed a new tower construction scheme, which reduces the material requirements and optimizes transportation and site assembly.

For the efficient operation of a wind turbine, an average wind speed of 5 to 6 m/s is required. The energy of the wind flow changes with the third power of wind velocity. Accordingly, the wind turbine tower height is dependent on the location and the hub height ultimately determines the economy of a wind turbine. Therefore, wind turbine manufactures have create different combinations of rotor diameters and hub heights to offer an optimal wind turbine depending on the location.

To reach the desired hub height, the construction of the tower is of particular importance. Self-supporting towers are mainly used for high-wind turbines. The tower is the largest and heaviest component of a wind turbine and represents approximately 20 to 25 % of the total cost. In addition, the tower has a big influence on the transportation and assembly costs.

The most popular tower types are lattice towers, steel tube towers, concrete towers, and now, for a few years, hybrid-towers. The hybrid-towers are a combination of a concrete tower with precast elements in the lower part and an attached steel tube tower in the higher part. Large hub heights of over 100 meters can be constructed at competitive costs using the hybrid tower concept (acc. [1]).

Fig. 1: Sketch of the Hybrid²-Tower

HYBRID²-TOWERS

CONSTRUCTION

The previously built hybrid-towers, which consist of a prestressed reinforced concrete tower and an attached steel tube tower, offer a considerable potential for improvement. The development of hybrid-towers is quite young, which is why there is still a considerable need for further advancement in this field.

The lower part of the concrete has a large self-weight. This should be optimized with regard to material requirements and assembly. Furthermore, the composite precast concrete towers are built of vertical and horizontal joints, which are prone to damage under dynamical loads. To minimize these problems, a hybrid-tower of precast reinforced concrete was developed.

A framework of concrete struts replaces a part of the concrete cross section so that an open tower section occurs for the base construction. With the combination of precast concrete and concrete framework, the lower portion itself becomes a hybrid-tower, on which a steel tube tower is attached. Thus, in a double sense, the combination of precast and strut concrete creates the so-called hybrid²-tower.

Fig. 2: View of the base of tower

[1]

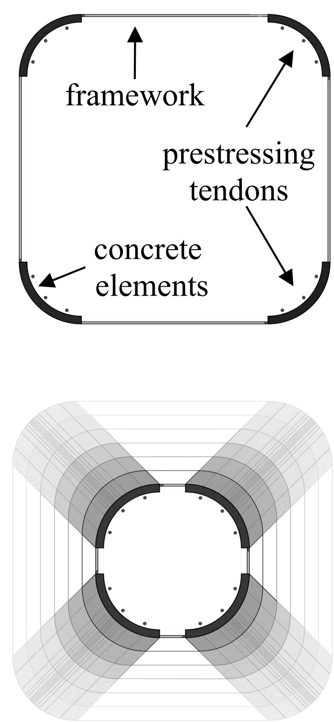

Fig. 3: Lower and upper cross-section of the tower

The new hybrid²-towers are built out of four prefabricated quarter-circle shaped concrete elements in the cross-section, which are connected by a precast strut framework. The quarter-circle shaped elements are 10 m high and are the same cross section for the complete height. Thus, it is possible to produce these elements in precasting plants with the same formwork. The weight of one 10 m element is less than 20 tons, which permits a delivery without special transportation equipment to the construction site.

The desired hub height determines the horizontal distance between each concrete element. The higher the tower, the greater the base contact area needs to be. The framework connects the concrete elements, thus the distances are variable. Moreover, the concrete corner elements are constructed with a slight inclination, so that the distance and the framework taper upward.

For example, a hub height of 145 meters, which is a usual size for hybrid-towers in Germany, requires a base area of 10 x 10 meters. Towers of this height dimension are built-up of a concrete tower, including a foundation and an adapter ring to a height of 85 meters, and the attached steel tube tower of 60 meters. Due to the modular construction concept of the hybrid²-tower and a height of 10 meters for each segment, different heights can be implemented easily. Because of the taper, a conventional steel tower with a diameter of about 4 meters can be attached to the top of the concrete tower with an adapter ring.

UHPC concrete bars will be used for the framework construction. The higher compressive strength of UHPC results in a reduction of the cross-section of the framework, which leads to material saving.

The assembling of each segment takes place on the ground. One segment consists of four corner elements and the concrete framework bars. The lower and upper end of each 10 m segment has a steel ring, to which multiple tasks are assigned. During assembly, the steel ring stabilizes the quarter-circle shaped concrete corner elements and ensures an accurate installation of the trussed framework bars. In addition, it can adjust to the tolerances in the corner elements. The steel ring shape is similar to the four quadrant cross sections. After each segment is assembled on the ground, it is placed on top of another segment and aligned with the aid of the steel ring. The horizontal joint between the overlapping steel rings is filled with grout. The surrounding steel constrains the lateral expansion of the grout and secures a force-fit connection.

Vertical external prestressing steel tendons are inside the tower, which set the concrete elements under compressive stresses and thus counter the occurring tensile forces from external load. The anchoring of the prestressing tendons is located in the foundation and in the adapter ring. The adapter ring is an important link between the concrete tower and the steel tube tower.

Further, the open structure of the framework offers creative advantages. In the standard version of the open framework, the tower is transmittance and can be integrated into the landscape. The open areas between the concrete elements can also be used for the design of the tower (acc. [1]).

FRAMEWORK

To connect the precast concrete corner elements to each other, precast concrete bars, made of UHPC, connect the corner panels like truss elements. This framework construction gives the hybrid²-towers its low weight and its open structure.

Therefore, the construction of the concrete framework bars is an important component of the tower. The concrete bars have to carry tensile or compressive forces in order to make the four corner pieces a composite structure.

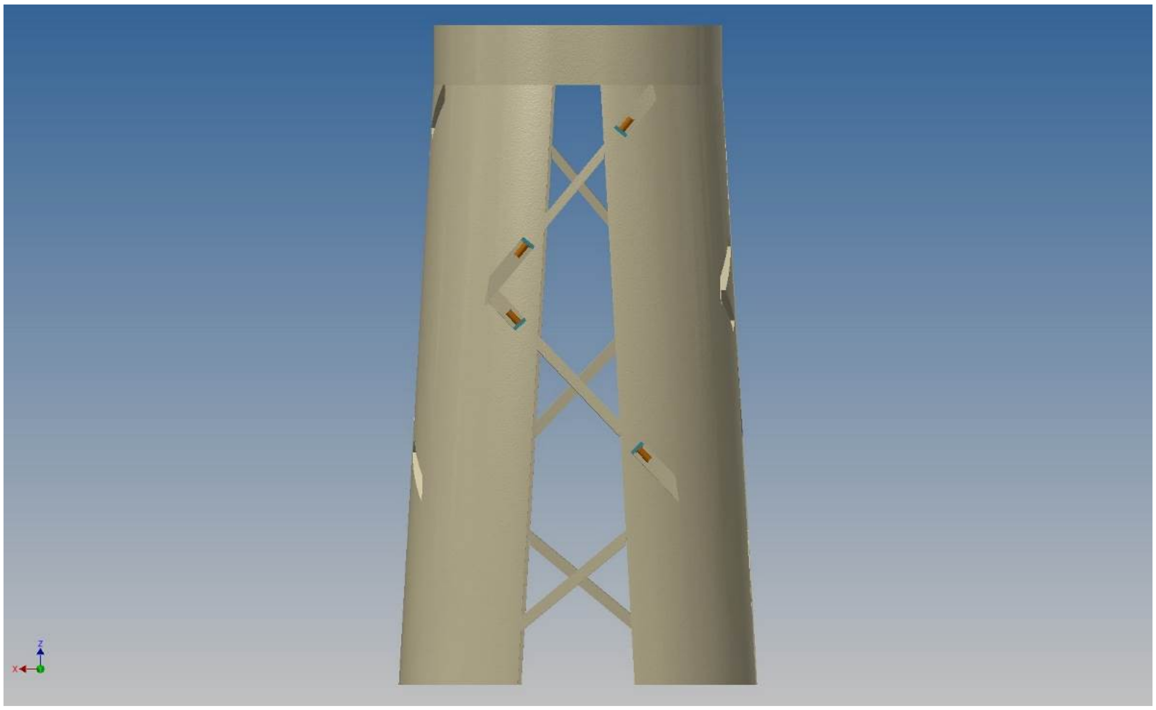

Fig. 4: Framework with prestressed concrete bars

The ultra-high performance concrete bars can be produced in a precast factory in the required lengths. At both ends of the concrete bars, steel plates are placed to adhere the flatness at the location of the connection. During the assembling of each tower composite structure, the concrete framework bars are arranged between the concrete corner elements on auxiliary structures. Grout is used for tolerance compensation between the concrete framework bars and the corner panels. Then the concrete framework bars are prestressed against the corner elements. The advantage of this type of assembling is the insensitivity to manufacturing tolerances.

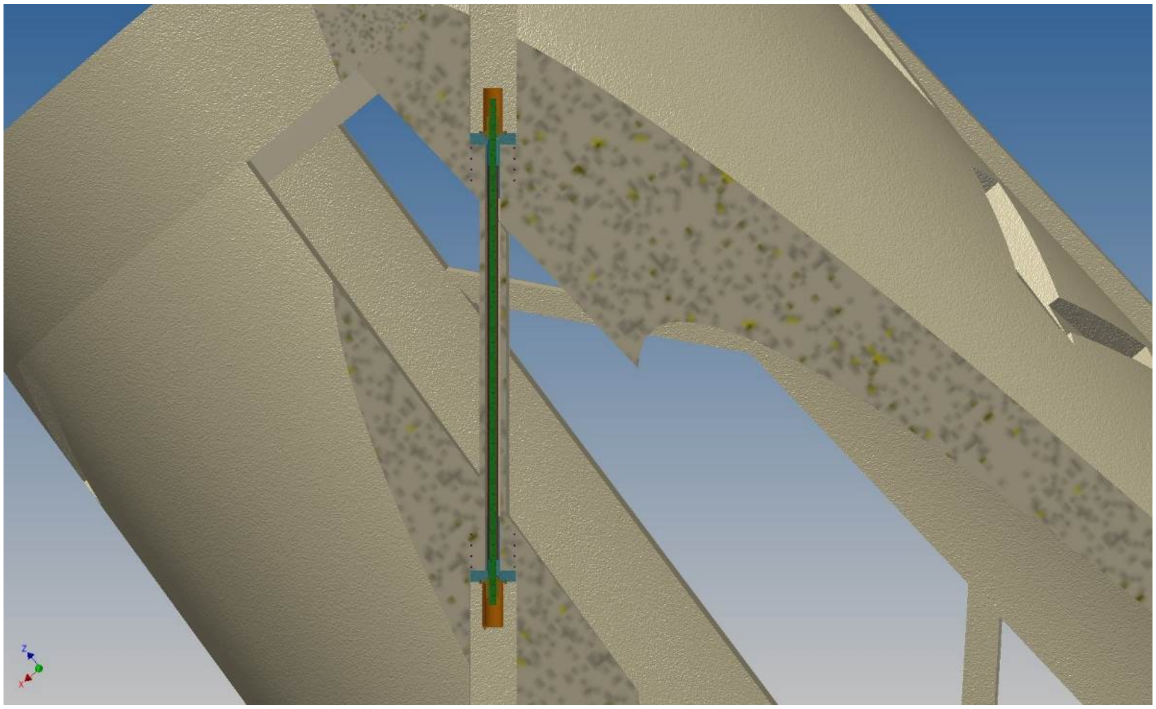

Fig. 5: Detail of a prestressed concrete bar

ULTA HIGH PERFORMANCE CONCRETE (UHPC)

CHARACTERISTICS

Ultra-high performance concrete has a particularly high structural stability. To get this characteristic, the amount of fines in the concrete is raised and the water to cement ratio is highly reduced in comparison to standard concrete. The strength of the concrete increases due to less pores giving it resistance to climate and chemical influences. The advantage of higher climate resistance could be used for concrete constructions for onshore wind turbine in comparison to normal concrete.

To get good workability of the fresh concrete, powerful plasticizers are needed to lower the water to cement ratio. Further, the post-failure behavior can be positively influenced by the addition of fibers (acc. [4]).

In general, the distinction of UHPC is based on the maximum grain size. Concrete mixtures with fine grain aggregates have a maximum aggregate size of about 0.5 mm, coarse concretes contain aggregates with a maximum grain size of 8 mm and have a lower percentage of sand and a higher proportion of coarse aggregate (acc. [2]).

Compressive Strength

The most important characteristic of UHPC is the high compressive strength of 150 to 250 MPa. However, the strength considerably depends on the mixture and on the curing (acc. [2]).

For example, a thermal curing with a higher temperature speeds up the chemical reaction and ensures a higher initial strength and a reduction of the autogenous shrinkage. Moreover, thermal curing changes the microstructure of the concrete significantly. The addition of fibers in the range of 0.5-3.0 % by volume enables an increase of strength of about 10-15 %.(acc. [3]).

In figure 6, the material behavior of UHPC without and with fibers is shown in a typical stress-to-strain diagram compared to normal concrete and high-strength concrete. Normal concrete has the lowest compressive strength and a very soft reduction in strength after failure. The compressive strength of high-strength concrete is higher than normal concrete and lower than UHPC. In contrast to normal concrete the strength reduces abruptly after failure. UHPC has the highest compressive strength. The fiber admixture positively influences the post-failure behavior of the UHPC. Under compressive stress, UHPC without fibers behave similarly to high strength concretes and show a sudden decrease of the load capacity when the compressive stress is reached, whereas concretes with fibers show a ductile material behavior.

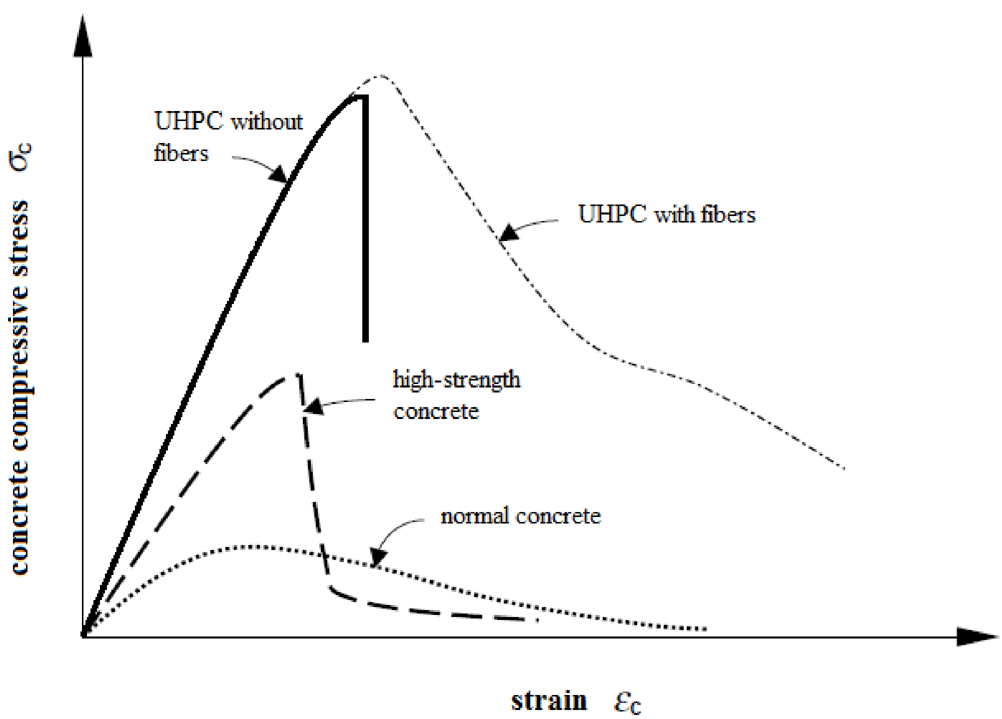

Fig. 6: Typical stress-to-strain diagram [3]

Tensile Strength

The tensile strength of concrete is a decisive characteristic concerning uniaxial tensile and compression loads. In case of axial tensile loads, the tensile strength is an important characteristic of the concrete. In the case of uniaxial compressive stress, the ultimate compressive strength is significantly influenced by the tensile strength, because the tensile strength dictates the ability to resist transverse expansions, the Poisson effect.

The tensile strength of UHPC is approximately 4 to 7 % of the compression strength. Compared to normal concrete, the tensile strength for UHPC is lower in relation to the compressive strength, which is approximately 10 % in normal concrete. The addition of fibers results in arresting cracking and decreasing the possibility of sudden failure under tensile loads.

In figure 7 the transition from micro cracking to macro cracking in concrete without and with fibers is shown in cross-section and in diagram. The diagram shows the course of transferable tension over crack formation.

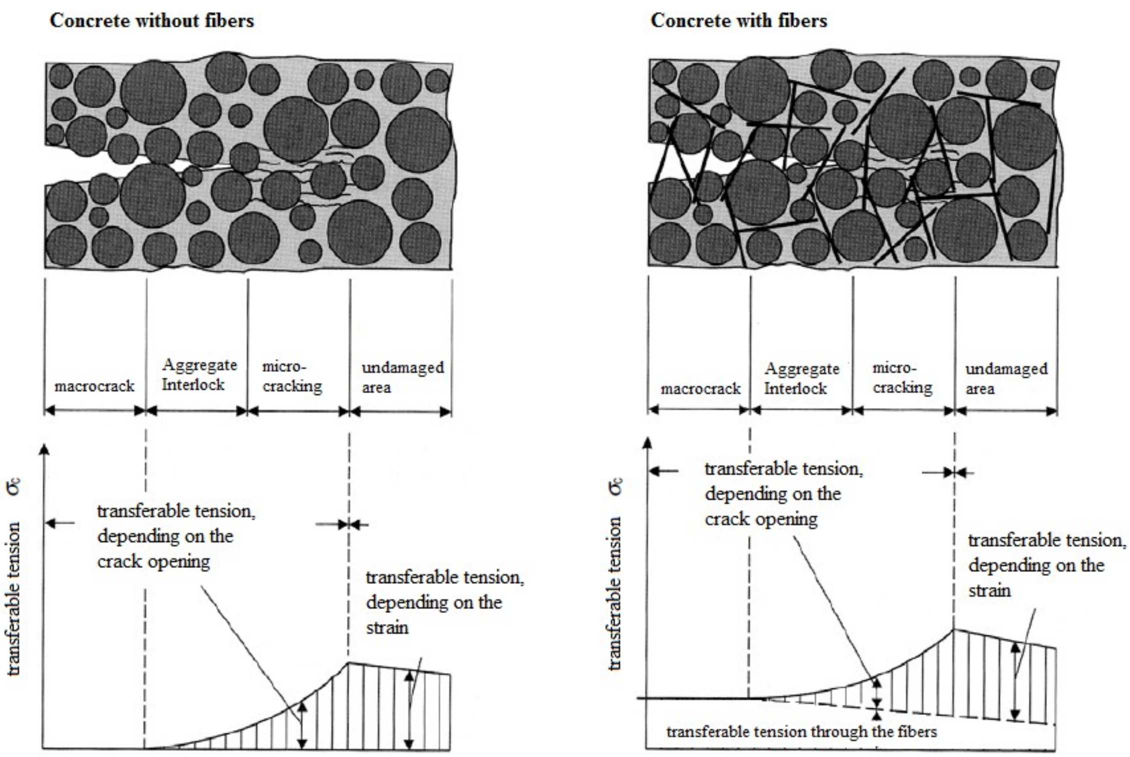

Fig. 7: Transition from micro cracking to macro cracking in concrete without / with fibers [3]

Modulus of Elasticity

The modulus of elasticity describes the resistance of concrete against elastic deformations. The modulus of elasticity of the concrete matrix is derived from the elastic modulus of the hydrated cement and the fin aggregate. Ultra-high performance concrete has a larger elastic modulus than normal concrete. It is from 45,000 to 60,000 MPa about twice that of normal concretes.

The higher modulus of elasticity increases the stiffness of a construction with the same cross-sectional dimensions in comparison to normal concrete. This result could be used in a double sense. On the one hand, to reduce the cross-sectional dimensions of the tower elements, which provides a weight and cost reduction for the precast elements. And on the other hand, to reduce the assembly costs by the use of smaller mobile cranes for the lighter precast elements.

The elastic modulus increases slower than the growth of compressive strength. A classification concerning the stiffness of ultra-high performance concrete to different materials is shown in the following figure.

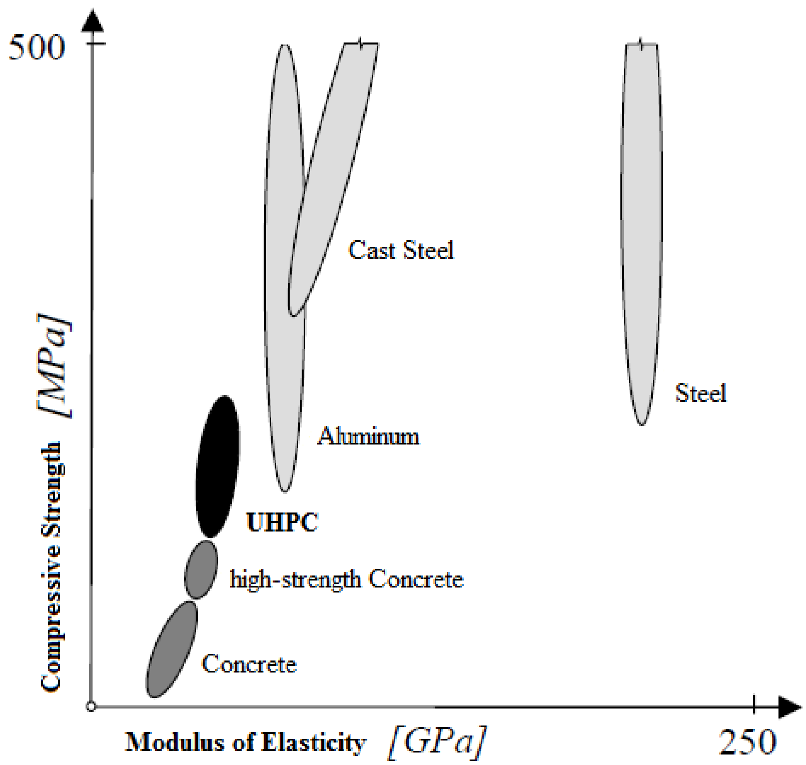

Fig. 8: Comparison of the strength and stiffness of different materials [4]

LABORATORY EXPERIMENTS

The suitability of ultra-high performance concrete for the concrete bars of the hybrid²-towers was verified in laboratory experiments. On the one hand, it was important to develop the characteristics of the concrete concerning the production of fresh concrete, the workability, and the curing. However, it was also important to create a concrete with a compressive cylinder strength of at least 130 MPa without the usage of thermal curing or immersion in water. The third concern was that the production and application for the hybrid²-towers should be as economical as possible.

For using conventional ultra-high performance concrete for engineering structures special high performance mixers are required for good homogeneity. Because conventional UHPC consist of fine-grained components that are not readily available and difficult to work with in conventional concrete plants. (acc. [2]).

The cement mixture Dyckerhoff NANODUR® Compound was used for the laboratory experiments. This Compound was produced for the production of ultra-high performance concrete in conventional concrete mixing plants. It consists of Dyckerhoff premium-cement NANODUR® CEM II/B-S 52,5 R and silica dust in a very fine flour consistency. With the help of the cement, that contains 59 % cement and 41 % silica dust, UHPC can be produced with common aggregates in conventional pan mixers which are comparable to concrete mixing plants in precast factories.

In the following table, you can see the mixture composition of the used coarse grain concrete.

Table 1: Mix design for 1 m³ UHPC

mass [kg]	**material**
430	pit sand 0/2 mm
880	high-grade chippings 2/5 mm
1.050	NANODUR® Compound 5941 grey
158,445	water
13,650	superplasticizer - BASF Masterglenium ACE 430 ρ = 1,06 kg/dm³

Three different mixtures of concrete were evaluated. The first mixture was made without fibers whereas the second and third mixtures used different quantities of fibers. The used fibers are made of steel with a diameter of 0.20 mm and a length of 6.00 mm.

- Test series E1 – mixture without fibers
- Test series E2 – mixture with 0.75 % fibers by volume
- Test series E3 – mixture with 2.5 % of fibers by volume

From each mixture, cubes, cylinders, and a slab were produced. The slabs were needed for coring out tension cylinders, which were used to determine the tensile strength. An advantage of the drill cores is the uniform fiber distribution in small specimen.The results of the experiments are listed in the following sub-chapters. They correspond to the mean values of all experiments.

Compressive Strength

The compressive strength of UHPC was determined by a servo-hydraulic universal testing machine. The tests were performed on cubes (w/t/h=150/150/150 mm) and cylinders (d/h=150/300 mm). To determine the post-failure behavior, the specimens were loaded in a displacement-controlled mode.

In figure 9 the cube specimens and in figure 10 the cylinder specimens in the servo-hydraulic universal testing machine after testing are shown.

[E1] *without fibers* [E2] *with 0.75 % fibers by volume* [E3] *with 2.5 % fibers by volume*

Fig. 9: Cube specimens after testing

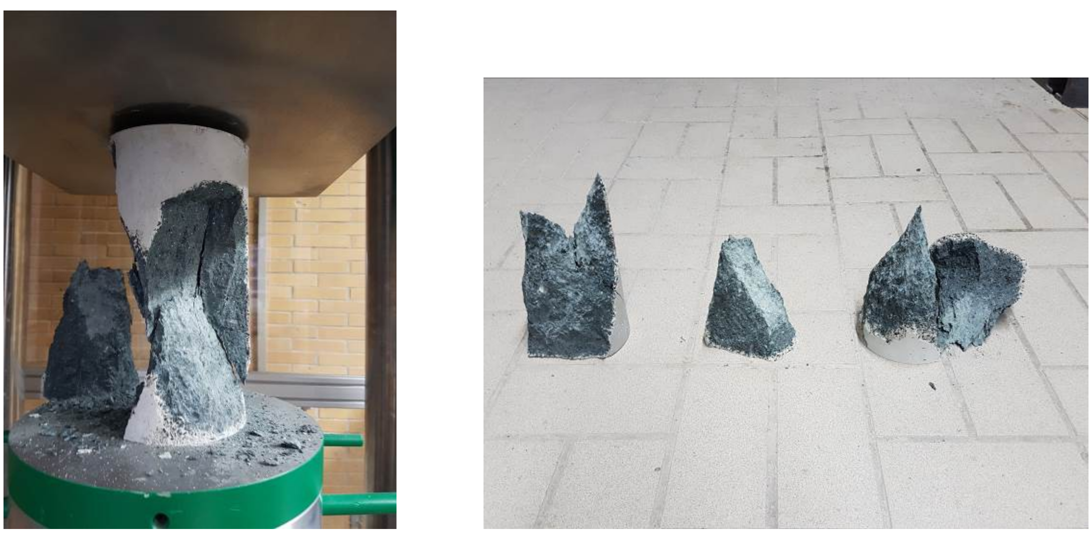

Fig. 10: Cylinder specimen after testing

All specimens reached a compressive strength greater than 130 MPa. The strength of the cylinders was similar to the cube strength. This result is in opposition to the difference between the compressive strength of cylinders and cubes of normal concrete, which are nearly 25 %.

In figure 11 and figure 12 the stress-to-strain diagram from the cube specimens and cylinder specimens are shown. The diagrams correspond to the mean values of all experiments. The admixture of fibers (series E2 and E3) caused no detectable increase of the compressive strength. Only the post-failure behavior of the cubes changed. The cylinders with and without fibers showed a sudden failure.

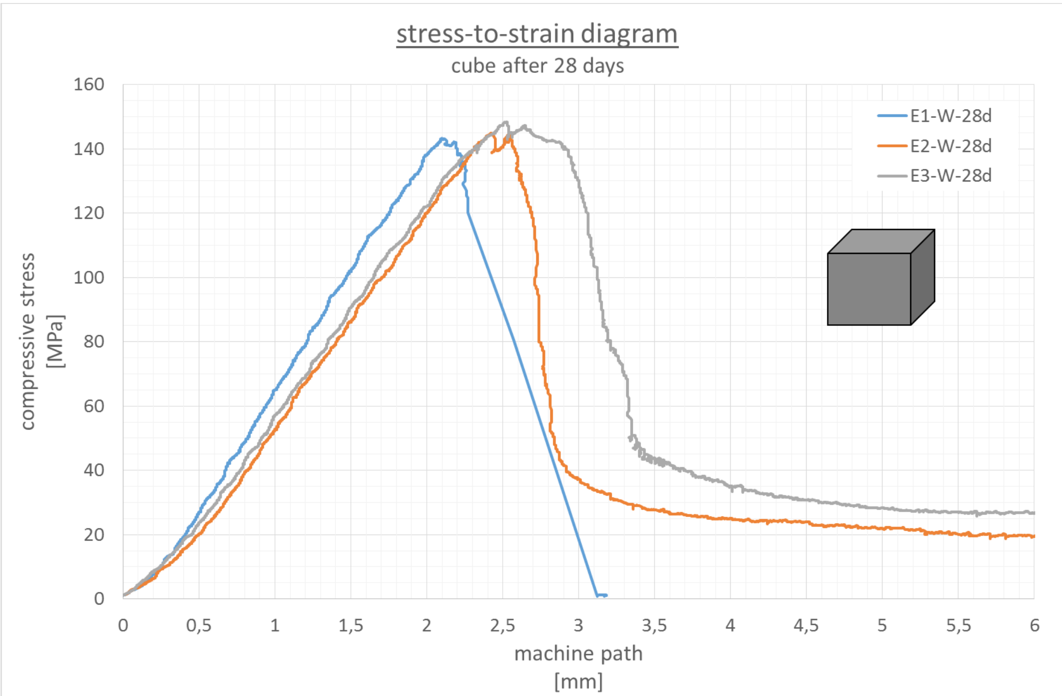

Fig. 11: Stress-to-strain diagram – cubes

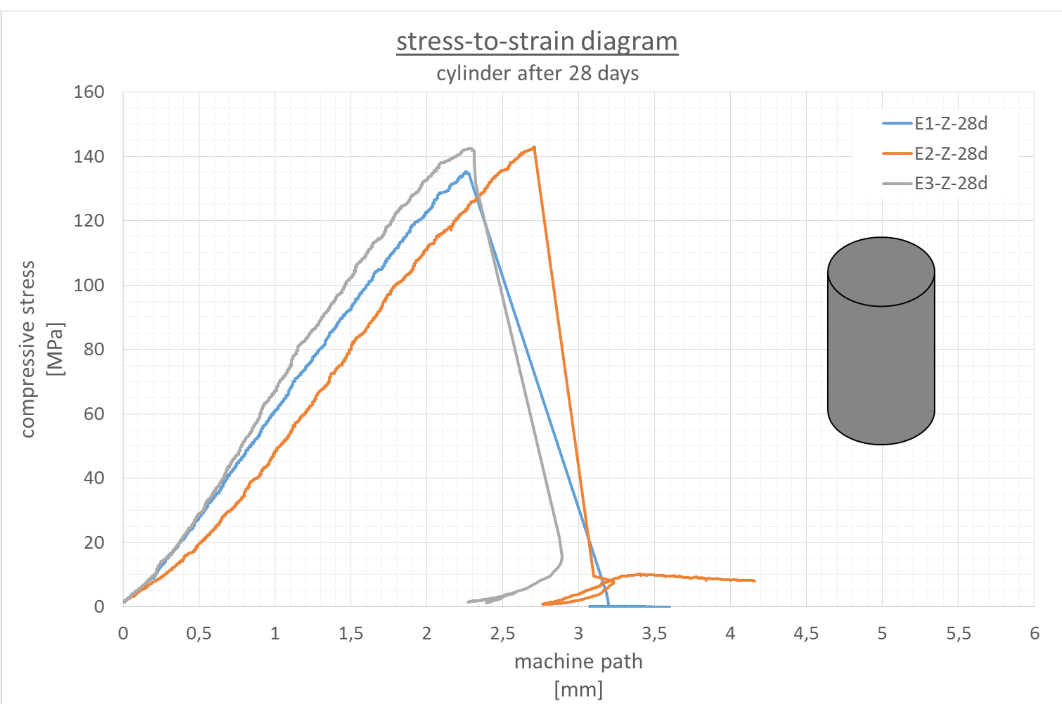

Fig. 12: Stress-to-strain diagram – cylinders

Tensile Strength

The axial tensile strength was determined on drilled cores with a nominal diameter of 50 mm and a nominal length of 150 mm. Linear variable differential transducers recorded the crack opening. To determine the post-failure behavior, the specimen were tested in displacement-controlled mode.

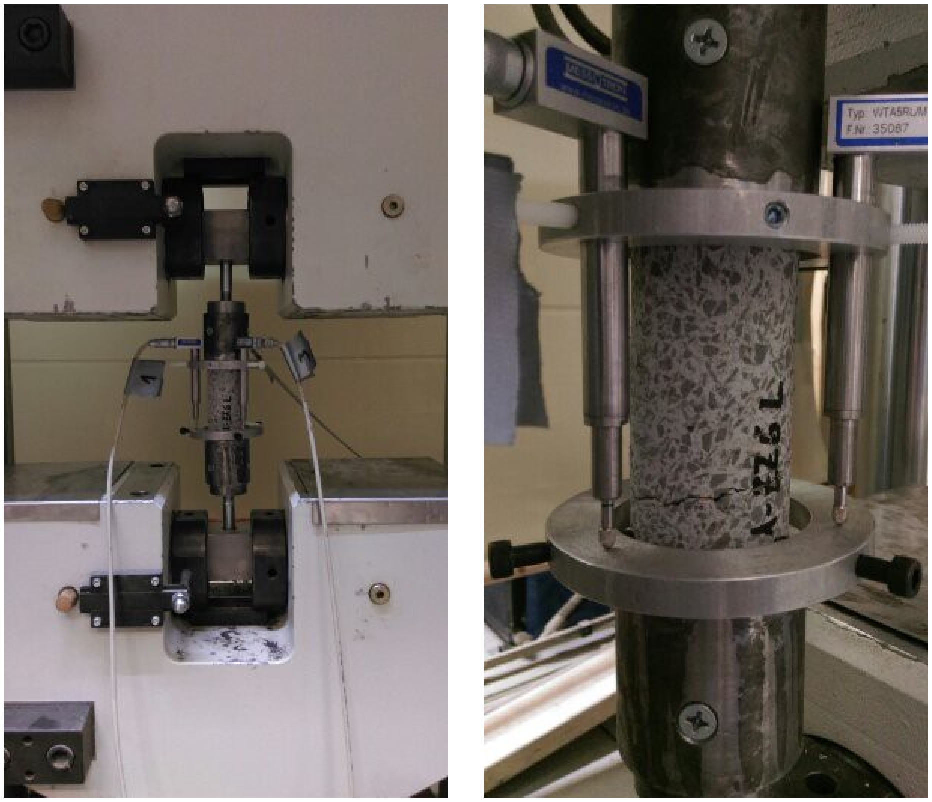

Fig. 13: Tension cylinder during the test

All specimens reached a tensile stress of 6.5-7.5 MPa. These values correspond approximately 4.5-5.5 % to the compressive strength of the prepared concrete samples.

In figure 14 the stress-to-crack opening diagram of the tension cylinders are shown. The diagram corresponds to the mean values of all experiments. The admixture of fibers (series E2 and E3) caused no detectable increase of the compressive strength. Only the post-failure behavior of the cubes changed. The cylinders with and without fibers showed a sudden failure.

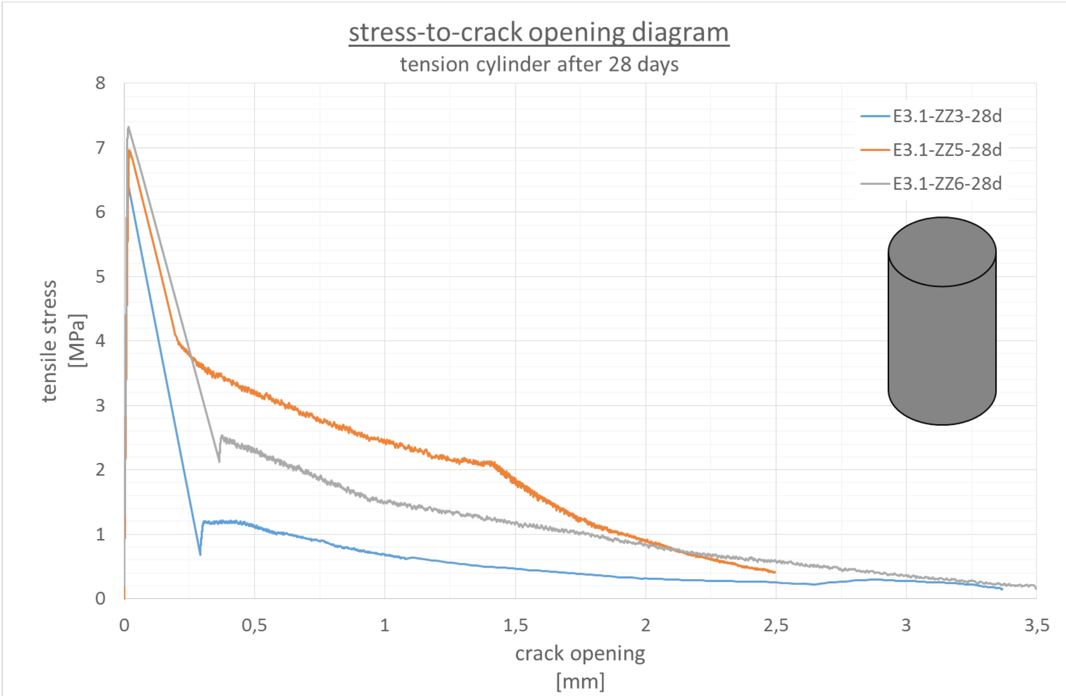

Fig. 14: Stress-to-crack opening diagram – tension cylinders with 2.5 % fibers by volume

Modulus of Elasticity

The modulus of elasticity in flexure from the hardened concrete was determined by a compression-testing machine. The tests were performed on cylinders with a nominal diameter of 150 mm and a nominal height of 300 mm according to DIN EN 12390-13 [5]. The average values of each experimental series are shown in the following table.

The values of the elastic modulus of all specimens and series are equal. No differences were found between the specimens without and with fibers.

Table 2: Average values of the elastic modulus

test series E1	test series E2	test series E3
E_{cm} = 52,654 MPa	E_{cm} = 54,102 MPa	E_{cm} = 52,826 MPa

CONCLUSIONS

The mission statement driving the development of the new hybrid²-towers for onshore wind turbines is to optimize the performance of the supporting-structure. In relation to structural optimization and cost saving, many advantages occur by using ultra-high performance concrete (UHPC) for the framework construction of the hybrid²-tower.

The conventional mixing of UHPC, made with a lot of fine concrete admixtures, such as silica fume and silica flour, needs high-performance pan mixers and special knowledge about processing and curing. Because of that, the practical application is severely restricted.

In laboratory experiments, the application of UHPC for practice was examined with usual coarse aggregate and a special cement compound in different conventional pan mixers, which are comparable to concrete mixing plants in precast factories. As a result, UHPC is applicable for practice and for concrete beams of hybrid²-towers. By using UHPC for the strut elements, the cross sections of the framework could be reduced, which leads to material saving and a more delicate structure. The material saving is associated with cost savings. On the one hand, less material is needed, which leads to cost savings despite the higher material price of UHPC. On the other hand, smaller dimensions reduce the weight of the precast elements, which leads to cost savings during assembling.

This investigation reviewed the necessity of producing UHPC with usual coarse aggregate in conventional pan mixers. Whereby the better characteristics of UHPC can be used compared to normal concrete. The results are not only important for onshore wind turbines. UHPC can also be used for building structures and engineering structures such as bridges or stadiums.

Furthermore, there is still a need for research in the field of fatigue strength. Wind turbines are subjected very large number of load cycle repetitions during their useful life. Material tests in the field of fatigue strength will be carried out in the near future.

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