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Winding Reinforced UHPC Sandwich Structures for Lightweight Jackets for Offshore Megastructures

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Winding Reinforced UHPC Sandwich Structures for Lightweight Jackets for Offshore Megastructures

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The paper presents a new type of cross-section for truss elements in an offshore construction's sub structure framework. By combining modern materials, such as ultra-high performance concrete (UHPC) and carbon fibre reinforced polymers in a hollow section, significant weight savings compared to conventional steel structures can be achieved. An extensive experimental programme has been carried out in order to describe the construction's load-bearing behaviour. The article presents an overview of the development process of the design, the methodological implementation of the experimental investigations and the results.

1. Motivation

Often, the dead weight of an offshore structure is the limiting factor in terms of transportation. Therefore lightweight constructions are needed to enable larger offshore constructions and to reduce costs. Ultra-high performance concrete delivers a high compressive strength and low self-weight compared to steel (see Tab.1).

Table 1. The ratio of absorbable compressive stress (σ_c) to density (ρ) illustrates the weight saving potential of the UHPC based on typical values. The results are displayed normalized to conventional structural steel.

Material	Density ρ [kg/m³]	Compressive stress σ_c [N/mm²]	σ_c / ρ [(N/mm²) / (kg/m³)] * 10²
Steel S235	7,850	235	3.0 **(≙ 100 %)**
Steel S420	7,850	420	5.4 **(≙ 179 %)**
UHPC (C200)	2,350	200	8.5 **(≙ 284 %)**

Aiming to make these unique properties usable for offshore foundations, strut-shaped load-bearing construction elements made of UHPC are being researched. These elements could be used as a basis for lightweight jacket foundations. In addition, the use of concrete instead of steel is preferable from the point of view of resource conservation and energy balance. In addition to the low dead weight, the load-bearing element must have a ductile behaviour in order to maintain the structure's resilience in case of failure of a single load-bearing element. The cross section's main component is a hollow UHPC-core. Due to the brittle fracture behaviour of UHPC, a new design concept was necessary to accomplish a ductile behaviour. By using carbon and sheet steel reinforcement, ductile component behaviour can be achieved. An externally applied carbon fibre reinforced polymers (CFRP) layer can be understood as winding reinforcement that helps to reduce the construction's steel amount in order to save weight and increases the construction's durability. Besides the UHPC's weight-saving potential, the new type of cross section has various advantages: A very high buckling stability is achieved due to the hollow cross-section; only much thinner sheets have to be welded than with conventional constructions; the cross section can be prestressed through the hollow core; the CFRP layer also acts as a highly effective corrosion protection.

Figure 1. The foundations of offshore (mega) structures account for a significant proportion of the total weight of the structure. Transporting the foundation structure is a logistical challenge. Weight can be saved on strut-shaped components by replacing steel cross-sections with concrete cross-sections.

2. Conceptual approach and development steps

At the *Intitut für Baustoffe* (Institute of Building Materials Science), different types of strut-shaped UHPC-load –bearing components have been developed. Starting with a pure UHPC-hollow section, UHPC tubular structures covered by steel sheets have been developed. The experience gained with these cross-sectional types led to the development of the new cross-sectional type on which this article focuses.

2.1. Pure UHPC-Core

For strut-shaped components subjected to axial compressive stress, the buckling stability is an important factor. In order to achieve a favorable ratio of material use to second moment of area (and thus for buckling stability), a resolved cross section (pipe cross section) is chosen. A round hollow profile is particularly suitable for this purpose, since second moments of area are equal in all directions. Round hollow cross-sections made of UHPC (see Fig. 1) are basically well suited to absorb axial loads and to provide high buckling stability at the same time.

UHPC shows a brittle behaviour that leads to an explosive failure behaviour (see Fig. 2). The brittle fracture behaviour is accompanied by a strong decrease of the absorbable force, as the cross section is reduced by bursting fragments.[1] UHPC is usually used in combination with a steel fibre reinforcement to maintain the ductility of the component. In the thin-walled cross-section, the steel fibres do not help to increase the ductility of the component.

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Figure 2. Test specimen (pure UHPC hollow section with steel fiber reinforcement) after testing the axial load carrying capacity. After reaching the maximum load-bearing capacity, no further loads could be applied. The residual load bearing capacity tends towards zero.

2.2. UHPC tubular structure covered by steel sheets ("UHPC hybrid tube")
For the reasons given above, even steel fibre reinforced UHPC cannot be used in thin-walled cross-sections without further reinforcement. Instead of conventional bar steel reinforcement, a different approach was adopted. The reinforcement is arranged in the form of two steel sheets inside and outside around the concrete core. The steel sheets serve simultaneously as lost formwork and as ductility increasing reinforcement. They are intended to provide lateral support for the concrete core after the component has reached and exceeded its limit load. Due to the lateral supporting effect of the steel pipes, the concrete core can still transmit axial compressive forces even in the fractured state and thus serves to maintain the residual load-bearing capacity of the component. The omission of steel fibres improves the processability.

Figure 3. UHPC hybrid tube specimen after testing the axial load carrying capacity. A buckling figure can be seen on the outer surface of the outer steel sheet. In this area the concrete core is locally destroyed. However, due to the lateral supporting effect of the steel sheets, normal forces can still be absorbed. The residual load is made up of different components. On the one hand, sheet steel reinforcement can absorb further normal forces and on the other hand, the broken concrete core can also transmit normal forces due to the lateral supporting effect of the sheet steel.[2]

UHPC hybrid tubes (see Fig. 3) show promising results regarding the load bearing capacity, put in relation to its dead weight. Compared to conventional steel constructions, a weight saving potential of 25 % up to 35 % is possible.[3]
In order to achieve a sufficiently high residual load, relatively high steel percentages are necessary. That leads to two significant disadvantages:

- The high steel content limits the weight saving potential of the components. The favourable properties of the UHPCS with regard to its low dead weight are partly compensated by the high steel content.
- Due to the higher stiffness of the steel (E_s = 210,000 N/mm²) towards the concrete steel (E_c = 50,000 N/mm²), axial loads are absorbed by steel sheets. The outer steel sheet reacts to this load with local buckling. It detaches itself from the concrete core at the base points. Thus

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it can no longer fulfil the task of reinforcement and the concrete core remains in these areas without a lateral supporting effect. This means that the residual load cannot be safely maintained.

2.3. UHPC tubular structure covered by steel sheets and winding reinforcement (winding-reinforced hybrid tube)

Winding-reinforced UHPC hybrid tubes represent a further development to the UHPC hybrid tubes (see Fig. 4). In order to reduce the steel content as much as possible, the structure of the UHPC hybrid tube is supplemented by a further component. On the outside of the outer steel sheet, a winding reinforcement made of a carbon fibre reinforced polymer (CFRP) is applied circumferential. This offers different advantages for the component: An exclusively horizontal orientation of the fibres leads to a high stiffness in the circumferential direction and to a negligible stiffness in the longitudinal direction.[4]

In this way, a particularly effective lateral support effect on the concrete core can be achieved. Due to the low axial stiffness, hardly any axial stresses are absorbed by the CFRP layer, so that local buckling of the CFRP layer is prevented. The low density (ρ_{CFRP} = 1.6 t/m³) of a CFRP compared to steel makes it possible to further reduce the dead weight of the component.

In combination with the roll reinforcement, the outer sheet steel is no longer used as a load-bearing component of the construction. It serves only as a lost formwork and as a "buffer" between the concrete core and the CFRP, as the carbon fibres of the CFRP are sensitive to transverse pressure. The lateral supporting effect is predominantly provided by the winding reinforcement. The thickness of the outer steel tube can therefore be chosen as thin as possible. The CFRP layer also serves as corrosion protection for the outer steel sheet. Thus an additional surface protection system can be dispensed with - it would already be part of the winding reinforcement.

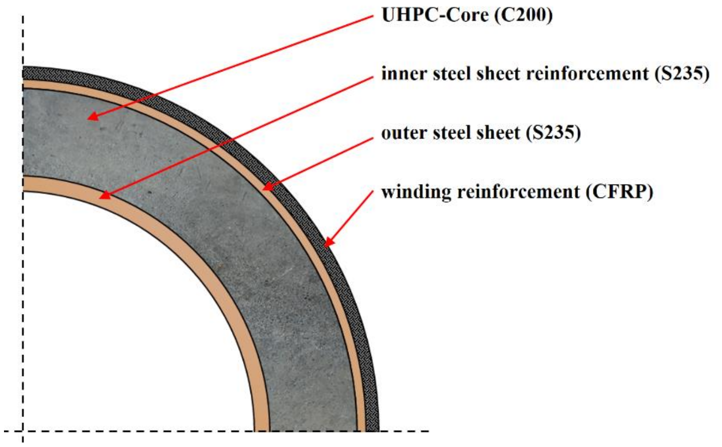

Figure 4. Structure of the cross-section of an element. The concrete core consists of a UHPC with a compressive strength of 200 N/mm², the steel sheets are made of conventional structural steel of grade S235. The CFRP consists of a carbon fibre (high tension, 400 tex) in a matrix of epoxy resin.

The functions of the individual components of a winding-reinforced UHPC hybrid tube can be summarized as follows:

- *Steel sheets inside*: lost formwork, reinforcement, lateral support of the concrete core
- *Concrete core*: absorption of axial compressive stresses
- *External steel sheets*: lost formwork, protection of the CFRP as a "buffer" layer
- *CFRP*: reinforcement (increase in residual load capacity), corrosion protection

3. Experimental Program

The aim of the work was to describe the load-bearing behaviour of the construction and to propose dimensioning rules. Different types of experimental investigations were carried out for this purpose. This chapter gives an overview of the methods used and the results of the individual test series.

3.1. Selection of a suitable fibre-reinforced polymer system (FRP)

Previous investigations and Lindschultes' dissertation have already provided information on the load-bearing behaviour of UHPC hybrid tubes without winding reinforcement. The investigations on UHPC hybrid tubes without winding reinforcement started on the material level. The aim of this part of the experimental investigations (see Fig. 5) was the selection of a suitable fibre-plastic composite system. Two essential requirements for the FRP were defined:

- a sufficient reproducibility of the results and
- a high radial stiffness (with low stiffness in longitudinal direction).

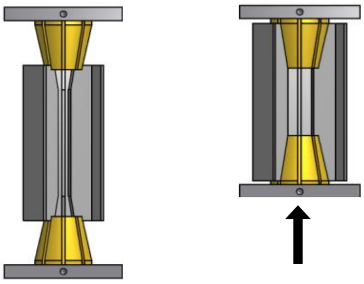

Figure 5. A test stand for radial expansion of cylindrical samples. The influence of the fibre angle and different material compositions on the radial stiffness of the samples was determined. The results were used to select a suitable FRP.

A unidirectionally wound CFRP (fibre orientation to 100 % in horizontal or circumferential direction) in epoxy resin showed the most favourable properties. The laminate was applied as a fabric by hand lamination. A radial stiffness of 60,000 N/mm² (20 % higher than the concrete's) was measured. The standard deviation for the 3 specimen population is 3,800 N/mm².

3.2. Centric compression tests on the entire cross section

After an FRP was selected, whole specimens were produced in two different sizes to quantify scaling effects. The aim of the experimental studies (see Fig. 6) was to investigate the influence of the winding reinforcement on the load-bearing behaviour of the entire component. For this purpose, the thickness of the winding reinforcement (t_{CFRP}) and the thickness of the inner steel sheet (t_{Si}) were varied. The thickness of the concrete core (t_C) and the thickness of the outer steel sheet (t_{So}) remained the same.

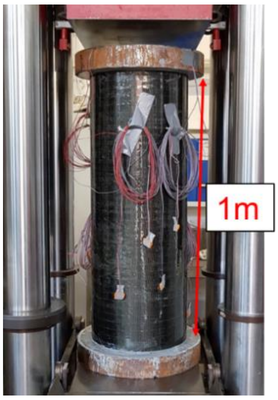

Figure 6. Medium-scaled specimen, built into the compression testing machine. In addition to displacement and force, strains were measured on the inside of the specimen (on the surface of the inner steel sheet) and on the outside (on the surface of the FRP). Load introduction plates are cast at the head and foot areas to ensure uniform load introduction and to prevent spalling.

The influence of the thickness of the winding reinforcements on the axial pressure carrying behaviour is tested on the basis of three series with different thicknesses of winding reinforcements (C06, C15 and C24). A series without winding reinforcement serves as a reference (C00). In another series (Ti40), the effect of a stiff inner core in the form of a 4.0 mm thick inner steel sheet (for all other series: $t_{S,inside}$ = 2.9 mm) to the load-bearing behaviour of UHPC hybrid tubes with different thicknesses of winding reinforcements were investigated.

The thickness of the roll reinforcement (t_{CFK}) refers to the fibre content, not to the complete structure of the CFRP incl. protective coating. The different thicknesses of the winding reinforcement is achieved by multiple wrapping of the UHFB hybrid tubes. For example, t_{CFRP} = 0.6 mm corresponds to two layers of carbon of 0.3 mm each, etc. The results of the small-format series are shown in Figure 7.

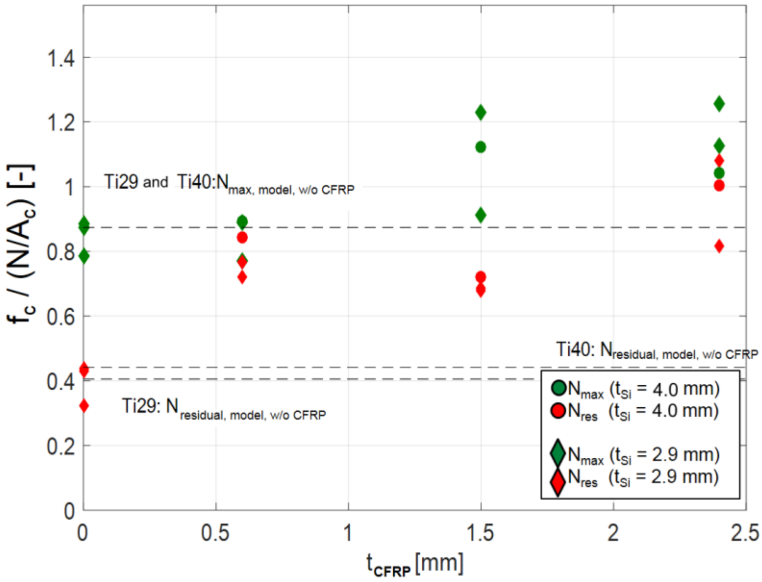

Figure 7. The results of the small-scale test specimens show the effect of the winding reinforcement on the maximum (green) and residual (red) load of the individual test specimens. The dashed lines are calculated values according to the Lindschulte model [2]. The respective load capacity is normalized by the compressive strength of the concrete as a function of the thickness of the winding reinforcement.

3.2.1. Winding-reinforced UHPC hybrid tubes without outer steel sheet

The results of the small-format series show that the winding reinforcement can be regarded as a highly effective type of reinforcement. Considering its effect as reinforcement, the outer steel sheet would therefore be superfluous. Based on this consideration, specimens were produced without outer steel sheet. The layer thickness of the CFRP was varied and the test specimens were checked for their axial load carrying capacity. An abrupt failure was detected in 3 of 6 specimens. The residual load bearing capacity of these specimens tended towards zero. When the maximum load capacity of the test specimen is reached, the concrete core fails first. This results in sharp-edged fragments that damage the carbon fibres, which are sensitive to transverse pressure. These can then no longer fulfil their function as reinforcement and an abrupt and explosive failure (see Fig. 8) of the test specimens occurs.

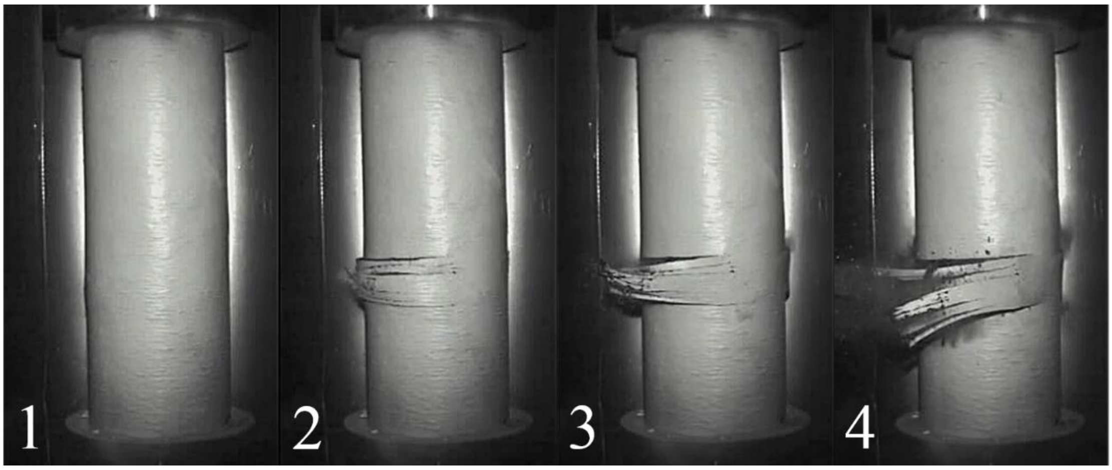

Figure 8. Explosive failure of a specimen without outer steel sheet.

3.3. Eccentric compression tests on the entire cross section

The winding-reinforced UHPC hybrid elements are intended to absorb predominantly normal forces in trusses. However, no bending stresses can be excluded, as no perfect framework exists. Bending stresses resulting in tensile stresses in the concrete should be avoided. For this purpose, the cross-section can be prestressed through the cavity interior without bonding. This results in a compressive stress condition in the concrete part of the cross-section, even with eccentrically introduced loads. The thickness of the winding reinforcement (t_{CFRP} = 0.6 mm and 1.2 mm) and the degree of eccentricity (eccentricity / diameter = 0.17 and 0.34) were varied in two steps each (see eccentric load introduction device in Fig. 9), so that a total of four series were investigated. Thus, it was possible to determine the influence of the winding reinforcement on the load-bearing behaviour of the specimens at normal force under superposition with a moment load.

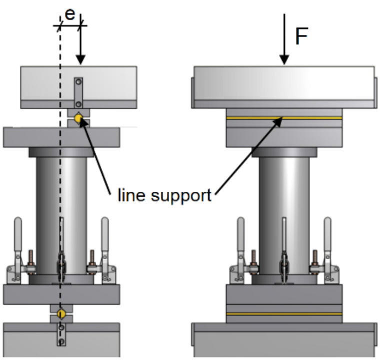

Figure 9. Device for eccentric load introduction

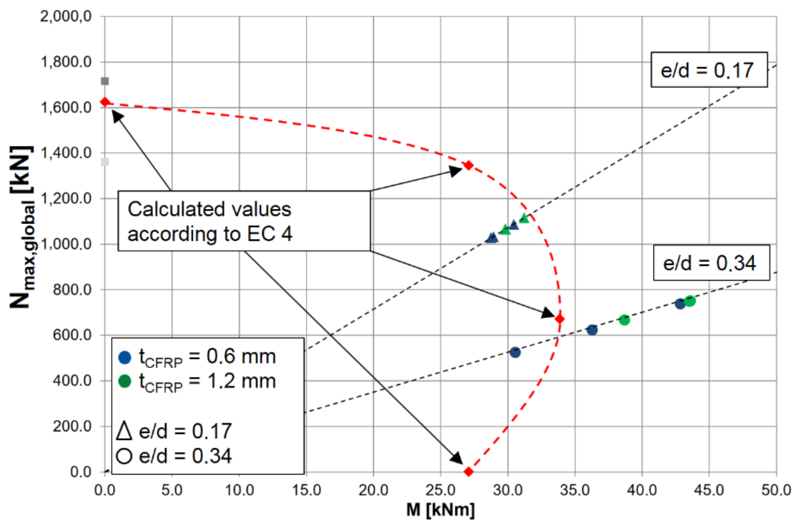

Figure 10. Interaction of bending and normal force. The red, dashed curve represents calculated values based on the dimensioning method introduced in Euro Code 4.

The results are shown in Fig. 10. In all cases, a relatively high residual load bearing capacity (over 80% of the maximum load) was observed. In principle, the results can be reconstructed using calculation procedures from Euro Code 4[5]. Without further adaptations, the procedure cannot be used safely, as measured values are below the calculated values.

4. Discussion of the results

4.1. Material tests on the CFRP

The dependence of the radial stiffness of the winding reinforcement on the fibre orientation can be determined with the test stand developed at IfB. As expected, a horizontal angle of application of the FRP is accompanied by a high radial stiffness of the layer. A hand laminated FRP shows reproducible results with a high radial stiffness. The reproducibility of the results is of great importance for a manually processed material, which is why this aspect was also taken into account when selecting a suitable FRP for further investigations on the entire cross-section. A high tension carbon fibre is chosen as the fibre material. The measured radial stiffness of glass fibres would lead to large layer thicknesses in order to ensure sufficient effectiveness as lateral reinforcement. With regard to processability, a two-component epoxy resin has worked well in all cases.

4.2. Centric compressive test on the whole cross section

The FRP selected in the previous step is applied to the outer surface of the UHPC hybrid tube construction described in Chapter 2.2. The efficacy is noticeable already at very thin layer thicknesses of 0.6 mm. Already two layers of 0.3 mm thick (200 g/m²) unidirectional CFRP increase the residual load capacity by 85%. The maximum load-bearing capacity remains as far as possible unaffected by the winding reinforcement or is subject to large fluctuations, so that an increase in the maximum force cannot be safely taken into account. It could be shown that the residual load is primarily dependent on the combination of internal steel sheet and winding reinforcement. The outer steel sheet between the concrete core and the winding reinforcement is required as a protective layer to prevent the carbon fibres from being damaged by the concrete core in the event of failure. This protective layer does not have to be made of steel sheets. It is also possible to use a textile protective layer between the CFRP and the concrete core. Corresponding concepts are currently being tested at the IfB.

4.3. Eccentric compressive test on the whole cross section

The design also proves to be effective for eccentric load cases. The measured values of the normal force are in some cases below the calculated values according to EC4. However, it can also be seen that the calculation method seems suitable as a first approximation. With regard to the ratio of the residual load carrying capacity to the maximum load carrying capacity, the eccentric load cases show uncritical behaviour. In all cases a relatively high residual load capacity was achieved. The detected ductility was higher than with the centrically loaded test specimens and the measured values for maximum and residual load scattered less. Compared to the eccentric load case, the centric load case is to be regarded as more critical and thus decisive for the dimensioning of the components.

5. Summary

The experimental results show that a winding reinforcement is a highly effective type of reinforcement. Although no safe increase in the maximum load could be achieved, the residual load-bearing capacity or ductility of the components can be increased by thin layers of winding reinforcement. In this way, weight savings of approx. 50% can be achieved (see Fig. 11) compared to steel structures. A component was developed which has great potential to further reduce the weight of offshore jacket foundations and thus enable even larger offshore megastructures.

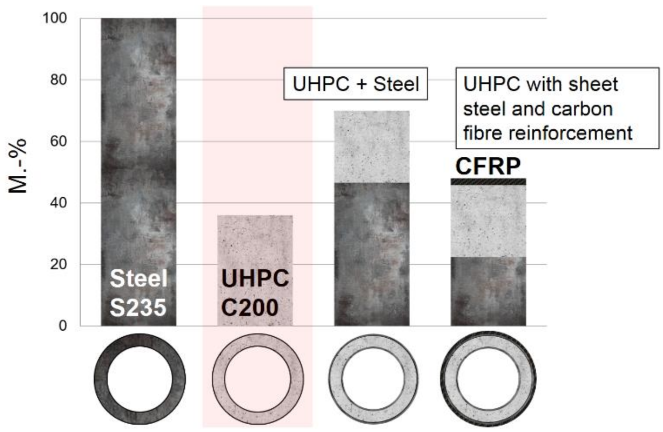

Figure 11. Weight proportions of the building materials of the components considered in this article. The weight for a constant normal force is displayed. The results are normalized using the weight of a construction made of conventional structural steel. The cross section made of pure UHPC is included only for the purpose of viewing. Due to the lack of ductility, it is not possible to build safely with pure UHPC without reinforcement.

5.1. Outlook

The main challenge on the way to UHPC lightweight jackets are the node connections. The manner in which the rod elements can be joined together should be the subject of subsequent investigations.

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