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UHPC SANDWICH STRUCTURES WITH COMPOSITE COATING UNDER COMPRESSIVE LOAD

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Abstract. Ultra-high-performance concrete (UHPC) sandwich structures with composite coating serve as multipurpose load-bearing elements. The UHPC's extraordinary compressive strength is used in a multi-material construction element, while issues regarding the concrete's brittle failure behaviour are properly addressed. A hollow section concrete core is covered by two steel tubes. The outer steel tube is wrapped in a composite material. By this design, UHPC is used in a material- and shape-optimised way with a low dead weight ratio[1] concerning the load-bearing capacity and stability[2]. The cross-section's hollow shape optimises the construction's buckling stability while saving self-weight. The composite coating on the column's outside functions both as a layer increasing the construction's durability and as a structural component increasing the maximum and the residual load capacity. Investigations on the construction's structural behaviour were performed.

Keywords: UHPC, sandwich structure, hollow tubular cross-section, composite materials, lightweight.

1. Introduction

The compressive strength of an ultra-high-performance concrete (UHPC) (f_c) exceeds 130 N/mm^2. Concrete with compressive strengths of 200 N/mm^2 can be unerringly produced. One of the challenges to face while working with UHPC is its brittle failure behaviour. Since abrupt failure of building components is to be avoided, constructive solutions have to be found.

This article addresses the design and mechanical system (see para.2.1) and the production (see para.2.3.2) of UHPC sandwich Structures with composite coating, while the individual materials are described in para.2.2.

The UHPC sandwich structures with composite coating exploit the concrete's properties and provide ductile structure behaviour, as proven in experiments (see paragraph 2.3).

A test set-up (see para.2.3.3) and results (see para.2.3.4) of axial compressive tests of specimens with and without composite coating are described. The results are discussed in para.2.3.4.

2. UHPC Sandwich Structures with Composite Coating

As shown in Figure 1, UHPC sandwich structures with composite coating consist of four layers of different materials. A hollow section UHPC core is covered by two concentrically arranged steel tubes which can be understood as lost framework and reinforcement of the UHPC core[3]. The outer steel tube is wrapped in a composite material layer. The composite layer fulfills different tasks: Its fibres act as a structural component (as described in para.2.1) and its matrix protects the outer steel tube's surface from corrosion.

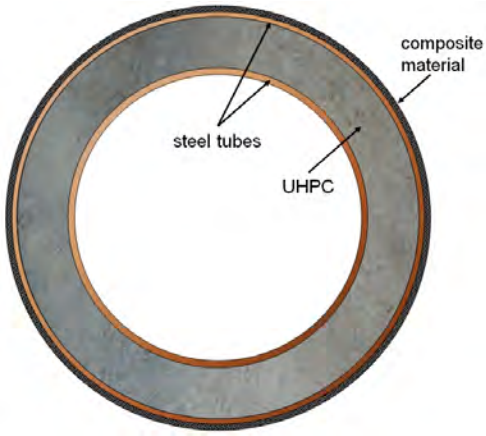

Figure 1. UHPC sandwich structure with composite coating, cross-section.

2.1. Mechanical System – Conceptual Approach

UHPC sandwich structures with composite coating serve as multipurpose load-bearing elements, predominantly for compressive loads. Axial loads are borne especially by the concrete's cross-sectional area. The inner and outer steel tube are ideally not involved in the axial load-bearing (as far as the serviceability limit state is not exceeded), nor is the composite material layer. Pure UHPC has the most favourable ratio of dead weight to compressive strength in comparison to steel. In order to increase the second moment of area and, thereby, the cross-section's buckling resistance, a hollow cross-section design is chosen.

Despite the UHPC's brittle failure behaviour, a ductile behaviour of the construction can be achieved by the interaction of the UHPC core and the construction's other layers. After exceeding the ultimate limit state, the construction is still able to bear further loads by the lateral supporting effects of the steel tubes and the composite layer.

The composite material's fibres are arranged in peripheral direction. Consequently, no axial loads are borne by the composite material while buckling and detachment issues are avoided as confinement effects increase both the construction's load-bearing capacities and its ductility.

Longitudinal strains of the columns under axial compression result in transverse strains. While the steel's Poisson's ratio is larger than the concrete's Poisson's ratio, peripheral tensile stresses occur in the concrete core. Radial expansions can be converted into peripheral stresses by the composite material's fibres, reducing the harmful tensile stresses inside the concrete core and, therefore, multiaxial compressive states of stress can be activated.

Due to these unidirectional properties of the composite material wrapping, the outer steel tube can be chosen with a relatively low thickness, resulting in further weight savings compared to conservative constructions.

2.2. Materials

2.2.1. Steel

Non-alloy quality steel, grade DC01, is used for the outer steel tube and conventional structural steel S235 is used for the inner steel tube. Both materials have a characteristic yield stress (f_y) of 235 N/mm^2.

2.2.2. Ultra-high Performance Concrete

The concrete's mix design and its basic material parameters are shown in Table 1 and 2.

Component	Type	kg/m^3
Cement CEM I	52.5R HS/NA	175
Microsilica	uncompacted	825
Fine Quartz Powder	50/16 μm	200
Sand	0.125/0.5 mm	975
Water	-	185
Superplasticizer	polycarboxylate	28
$W/C = 0.24$	Water to cement ratio	
$W/B = 0.20$	Water to binder ratio	

Table 1. The design of the concrete mix used.

Average density	2.323	kg/dm^3
Slumpflow (SF) (1)	900	mm
Compressive strength (2,3)	220.0	N/mm^2
Flexural strength(2,4)	13.3	N/mm^2

(1) According to DIN EN 12350-8[4]
(2) After thermal treatment at 90 °C for 48 h, started 24 h after casting, cube 100 × 100 mm
(3) According to DIN EN 12390-3[5]
(4) According to DIN EN 196-1[6]

Table 2. The basic material parameters of the concrete used.

2.2.3. Composite Material

The carbon fibre reinforced plastic composite consists of

- a unidirectional carbon band, which is aligned in the peripheral direction of the specimen (see Fig. 2) and
- a matrix of epoxy resins, which is predominantly used for rotor blades for wind turbines and shipbuilding.

Carbon band	
Material	Carbon Fibre (HT)
Width	25.0 mm
Thickness	0.3 mm
Weight	350.0 g/m^2
Yarn Count	400.0 tex
Matrix	
Epoxy resin	*Hexion Epikote*
Epoxy hardener	*Hexion Epikure*
Heat-curing	12 h, 70 °C

Table 3. The composite material used.

Figure 2. Unidirectional carbon fibre band

2.3. Experimental Research

In order to demonstrate the composite material layer's impact on the mechanical system, the maximum load-bearing capacities of specimens with fibre reinforced plastic composite coating (Series B, two specimens) are compared to those of specimens without composite coating (Series A, three specimens).

2.3.1. Specimen Geometry

The specimen's properties are shown in Table 4.

2.3.2. Production of the Specimens

In a first step, the steel tubes are aligned perfectly concentrically. Afterwards, the concrete is placed by means of a tremie pipe (contractor method).

After heat curing the concrete (see para.2.2.2), the composite material is applied onto specimen B in a hand lay-up process by means of a mounting fixture that allows rotation around the longitudinal axis. In a last step, the composite material is heat cured. A specimen of Series B is shown in Figure 3.

Series A:	without composite layer
Inner steel tube:	$\varnothing_{outside} = 133.0\ mm$
	$t_s, inner = 2.9\ mm$
Outer steel tube:	$\varnothing_{outside} = 169.0\ mm$
	$t_s, outer = 1.0\ mm$
Concrete core:	$\varnothing_{mid-line} = 155.0\ mm$
	$t_c = 19.2\ mm$
Length:	$l = 500\ mm$
Weight:	$m = 15.39\ kg$
Series B:	with composite layer
Composite Material:	8 layers of carbon band
	$\approx 3.0\ mm$ (inc. matrix)
Weight:	$m = 16.64\ kg$
in all dimensions as Series A	

Table 4. Properties of the two series

Figure 3. Specimen of Series B

2.3.3. Test Set-up

The experimental work focuses on the maximum load-bearing capacity and the ductility. The specimens are loaded in a displacement-controlled (load speed 0.25 mm/min) test by a hydraulic cylinder to failure and beyond. An integrated calotte levels possible tilting. Normal force and displacement are measured. In order to introduce the load predominantly into the concrete core and to avoid cracks in the load introduction area, the specimens are grouted in a load introduction panel. The same concrete mix design as used for the specimen is used as grout material. Figure 4 shows the test set-up containing the specimen, the load introduction panels, three inductive displacement transducers and protective equipment.

2.3.4. Results

Table 5 shows the results for all specimens of Series A and B. Force–distance diagrams for two selected ex-

Figure 4. Experimental set-up

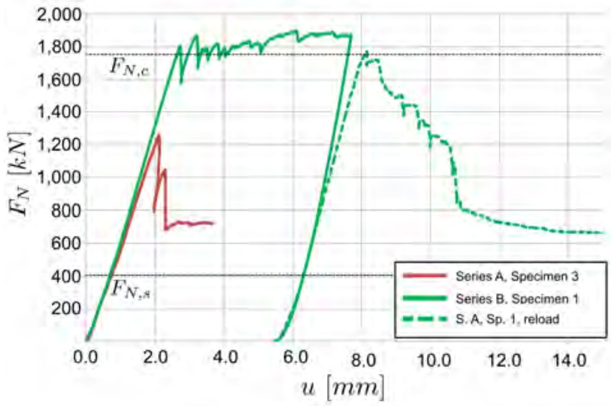

Figure 5. Force–distance diagrams, two selected examples

	F_N, max	F_N, residual
Series A, Specimen 1	$1,395\ kN$	$554\ kN$
Series A, Specimen 2	$1,389\ kN$	$675\ kN$
Series A, Specimen 3	$1,260\ kN$	$684\ kN$
Series A Average	$1,348\ kN$	$638\ kN$
Series B, Specimen 2	$1,774\ kN$	$1,610\ kN$
Series B, Specimen 2	$2,073\ kN$	$950\ kN$
Series B Average	$1,924\ kN$	$1,280\ kN$

Table 5. Results of the experimental research

amples are presented in Figure 5. Positive F_N-values represent compressive forces for means of presentation.

Figure 6 shows the two specimen after testing. The broken concrete core of the specimen shown causes a buckling formation on the outer steel tube. The inner steel tube (not shown in Fig. 6) is also affected. The buckling appeared when the maximum load capacity of $1,260\ kN$ was reached.

The specimen of Series B shown appeared to be undamaged from the outside until a displacement of 10.0 mm is reached. At this point, only single sectors of the composite material failed to a limited extent. When the displacement reached 10.0 mm, a larger amount of fibres failed, causing an extensive detachment in the specimen's middle section. Under the composite layer, the outer steel tubes showed buckling formations that are comparable to those of specimen A.

Figure 6. Series A specimen 3 (left) and Series B specimen 1 (right) after testing

3. Discussion

As the results show, the maximum load-bearing capacity and the residual load-bearing capacity of UHPC Sandwich Structures can be increased by the addition of a composite layer. The ductility (in this context, the ratio of the residual force to the maximum force) is affected as well, but the results differ. While the ductility of specimen 1 of Series B can be increased significantly (the residual force is at 90 % of the ultimate load), the residual force of specimen 2 is at 59 % of its ultimate load. It is still higher than the average ductility of the specimens of Series A (47 %), but, in view of the large variation, the effect is negligible. It is assumed that different modes of failure are the reason for this variation. While the concrete core of specimen 1 fails first and is still supported laterally by the composite material, it is suggested that in the case of specimen 2, the fibres fail first and lead to a sudden drop in the load-bearing capacity (from $2,073$ to 950 kN) bearing capacity.

Table 6 shows a simple approach to estimate the construction's load-bearing capacity. The composite layer is not taken into account because of its peripheral fibre orientation.

Cross-sectional area (Specimen A and B)	
Steel tubes:	$A_s = 1,713\ mm^2$
Concrete core:	$A_c = 7,959\ mm^2$
Load-bearing shares (simple assumption):	
$F_{N,s} = A_s * f_y = 402.4\ kN = 16.7\ \% * F_{N,\text{total}}$	
$F_{N,c} = A_c * f_c = 1,750.9\ kN = 81.3\ \% * F_{N,\text{total}}$	
$F_{N,\text{total}} = F_{N,s} + F_{N,c} = 2,153.3\ kN$	
Load-bearing capacity (experimental results):	
Specimen A:	F_N, average $= 1,348\ kN$
Specimen B:	F_N, average $= 1,924\ kN$

Table 6. Maximum load-bearing capacity estimation, simple approach

The construction's maximum load-bearing capacity is overestimated by the simple approach. The reason for this could be

- the load introduction by load introduction panels that exclude loads partially from the steel tubes;
- effects caused by stability; or/and
- imperfections (material and geometry).

Lindschulte proposes a more sophisticated estimation model (eq. 7-1[2]) for sandwich structures without composite coating:

$$F_N = A_c * 0.8 * f_c + \alpha_{s-1} * A_{s,-1} * f_y + \alpha_{s+1} * A_{s,+1} * f_y \quad (1)$$

where is

$A_{s,-1} =$ Area of the inner steel tubes cross-section

$A_{s,+1} =$ Area of the outer steel tubes cross-section

$\alpha_{s-1} =$ Stability reduction factor concerning to $\chi(\lambda)$ according to Eurocode 3, inner steel tube

$\alpha_{s+1} =$ Stability reduction factor concerning to $\chi(\lambda)$ according to Eurocode 3, outer steel tube

Applying Lindschulte's model to the series' geometry shown leads to

$$F_N = 1,400\ kN$$

assuming a non-load-bearing role of the steel tubes. This estimation fits the experimental results of Series A ($F_{N,\text{average}} = 1,348\ kN$) well. The increase of the maximum load-bearing capacity of Series B cannot be explained with this model.

Confinement effects as a result of the composite layer have to be considered as a reason for this. The composite material's fibres bear tensile stresses in a peripheral direction, that are caused by transversal strains in a radial direction under axial compression. Without these fibres, these radial strains lead to tensile stresses in the concrete-core. Due to the confinement effect, all compressive stress states in the concrete core are reached, leading to a higher maximum load-bearing capacity.

Both specimen of Series B also have a higher residual load-bearing capacity. This can be explained by the lateral supporting effect of the composite material. After the concrete is broken, it is kept in place by the inner steel tube and the outer steel tube, which is additionally supported by the composite material.

4. Outlook

UHPC sandwich structures with composite coating could be beneficially used, for example, in large frameworks of offshore megastructures[7]. In order to prove the concept, further investigations have to be performed. The following subjects require special attention:

- The identification of different failure modes.
- Numerical simulations to prove the mechanical behaviour assumed.
- Further experimental research with different geometries in order to derive a model for the prediction of the maximal load and the residual load.
- The component's behaviour under pure bending and bending with normal force.
- The component's behaviour under cyclic load.
- Junctions and load introduction.

List of symbols

ε strain [–]
A_c concrete area [mm^2]
A_s steel area [mm^2]
F_N maximum normal force [kN]
$F_{N,c}$ normal force, concrete's share [kN]
$F_{N,s}$ normal force, steel tubes' share [kN]
f_c concrete's compressive strength [N mm^{-2}]
f_y steel's yield stress [N mm^{-2}]
u displacement [mm]
W/C water to concrete ratio [–]
W/B water to binder ratio [–]

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