Composite Structures made of Ultra-High Performance Concrete and Fiber-Reinforced Polymers

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ABSTRACT: The ambition of this study is the development of innovative composite structures made of steel-fiber reinforced Ultra-High Performance Concrete (UHPC) and Fiber-Reinforced Polymers (FRP). The new composite construction method is characterized by low self-weight, high durability and simplicity, and could represent a robust alternative to prefabricated steel, timber or normal concrete elements. Within the study, two different types of composite structures are investigated: composite structures consisting of UHPC and structural profiles made of Glassfiber-Reinforced Polymers (GFRP), as well as UHPC structures with reinforcement made of Carbonfiber-Reinforced Polymer (CFRP) lamellae. For evaluation of feasibility, a comprehensive theoretical and experimental research into the bond and bending behavior of UHPC-FRP composites is carried out and several structural building applications like beams, shells and façade elements are investigated.

1 INTRODUCTION TO MATERIALS

The use of UHPC in structural design is a relatively new trend and started at the end of the 1980th in Canada and France. Its structural behavior is currently being scientifically tested all over the world in combination with different kinds of reinforcement. The enormous compressive strength and the excellent bond properties allow the design of extremely slim and filigree structures comparable with steel constructions, as well as the use of high strength reinforcement. However, the combination of UHPC and FRP, which are characterized by outstanding tensile strengths, has not intensively been investigated in science up to now.

FRP are also rather new materials in building industry and mainly used for tension cables, post strengthening of constructions and reinforcement in aggressive environments. Structural FRP products are manufactured in a pultrusion process, which ensures high fiber content and constant quality. They represent a corrosion resistant and light alternative to steel components and the standard product range covers all kinds of profiles like angels, tubes and double-t beams.

1.1 *Ultra-High Performance Concrete*

UHPC is characterized by compressive strengths up to over 200 N/mm², high resistance against environmental influences and great freedom in geometric shape due to its good flow and self-compacting properties. The superior performance is obtained with low water cement ratio, optimization of grain mixture and heat treatment after solidification. Unfortunately, elastic modulus and tensile strength do not increase at the same rate as compressive strength and the material becomes increasingly brittle. Furthermore, the material shows growing linear stress-strain behavior until material failure and a steeply falling working line after concrete cracking (Koenig, 2001).

For improvement of mechanical properties, UHPC is usually reinforced with short steel fibers. They do not have a significant influence on the mechanical properties of non-cracked concrete, but with increasing crack formation, the structural behavior is positively influenced: they improve the flexural strength by transferring tensile forces over the crack and prevent the explosive failure mode under compression, which is typical for high strength concrete without fibers (Koenig, 2001).

In Table 1 the mechanical properties of normal concrete C25/30 and typical UHPC are compared. It shows that UHPC´s compressive strength is about 8 times higher than normal concrete´s, whereas tensile strength and elastic modulus are only about 4 and 1.3 times higher. Specific weight and thermal expansion coefficient of normal concrete and UHPC do not differ strongly.

Table 1. Mechanical properties of normal concrete C 25/30 (EN 1992-1-1, 2009) and UHPC with 2.5 vol.-% steel fibers (DAfStb, 2008).

Characteristic values	Concrete C25/30	UHPC
Specific weight [kN/m³]	25	25
Elastic modulus [N/mm²]	31 000	46 000
Compressive strength [N/mm²]	25	200
Breaking strain [‰]	3.5	4.8
Tensile strength [N/mm²]	2.6	10.0
Thermal expansion coefficient [10^{-6}/K]	10	11

1.2 *Fiber Reinforced Polymers*

FRPs are composite materials that consist of fibers and polymer matrix. They have a distinctively orthotropic behavior, in which the fibers control the mechanical properties in fiber direction and the matrix normal to. The matrix fixes the fibers in space and introduces loads, the fibers have the function to transfer loads in span direction.

Glass- and carbonfibers are most widespread among all FRPs. They have high tension and compression strength and high breaking elongation. Glassfibers are furthermore incombustible and have good resistance to chemical and biological aggressions. Their weakness is the low elastic modulus. Carbon fibers have even more outstanding mechanical properties, but are enormously expensive as well. The matrix is commonly made of unsaturated polyester, vinyl ester or epoxy resins. Polyester and vinyl ester are cheaper than epoxy, however, they do have lower strength properties (Schuermann, 2007).

In Table 2 the mechanical properties of steel, GFRP and CFRP are compared. It shows that FRPs have an almost 40 times lower specific weight and a 200 times lower thermal conductivity than steel. The elastic modulus of GFRP is about 5 times lower than steel, whereas CFRP reaches almost the same stiffness values as steel. The FRPs´ tensile strength is up to 8 times higher than steel, however, the breaking strain is approximately 15 times lower due to the lack of a plastic yield range.

Table 2. Mechanical properties of different materials (Peters, 2009), (Bank, 2006), (Sika, 2009).

Characteristic values	Steel S 235 JR	GFRP rebar	CFRP lamella
Specific weight [kN/m³]	78.5	2.1	1.6
Elastic modulus [N/mm²]	210 000	41 000	165 000
Tension strength [N/mm²]	360	620	3 100
Breaking strain [%]	26	1.6	1.7
Thermal expansion coefficient [10^{-6}/K]	11.7	6.7	0.7
Therm. conductivity [W/mK]	50	0.25	nr*

* not reported by manufactures.

2 PROBLEM DEFINITION & AIM OF STUDY

The fundamental problem with using UHPC as a structural member is the handling of its low tensile strength and the utilization of its enormous compressive strength. In accordance with normal concrete, there are actually three ways to deal with tensile stresses:

- reinforcing the tensile stressed areas,
- pre-stressing the construction to suppress tensile stresses or
- choosing a constructions with low bending stresses and/or improving concrete´s tensile strength by using special types of cement.

In this study, the first approach is followed by reinforcing the UHPC with FRP. The reason behind this decision is that this method is corrosion resistant, technically simple and does not have a strong influence on the structure´s form.

The aim of this study is the development of efficient UHPC-FRP composite structures with a balanced ratio between compressive and tensile strength, which are able to utilize the high resistance of both materials, as shown in figure 1.

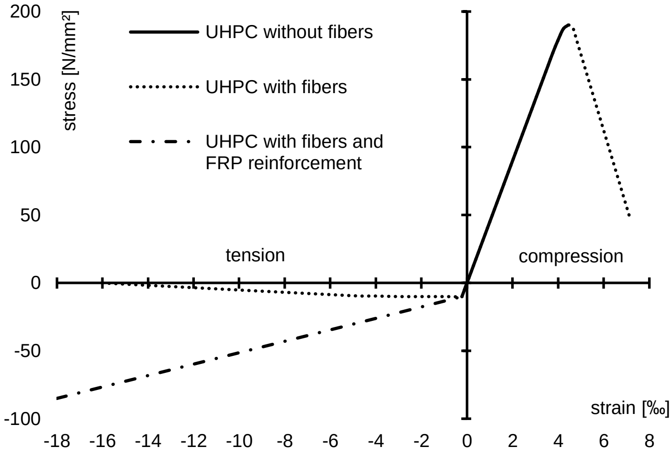

Figure 1. Qualitative stress-strain relationship of UHPC with different kinds of reinforcement under centric tensile and compressive load (DAfStb, 2008).

3 WHY UHPC AND FRP?

Within this study, two different types of composite structures are investigated: composite structures made of UHPC and GFRP structural profiles, and UHPC structures with reinforcement made of CFRP lamellae. Since GFRP are rather cost efficient, they can be applied to composite structures intensively in form of structural profiles. CFRP, however, are more cost intensive and therefore must be used very economically in form of thin lamellae.

In both cases, the material combination appears useful for several reasons:

- Due to the good bond properties of UHPC, shear force transmission between UHPC and FRP is solely done by friction and adhesion, which is improved by roughening the FRP-surface. No additional mechanical joining means are required.

• The compact UHPC protects the FRP components against harmful environmental influences and improves the fire resistance. FRP has the advantage of being corrosion resistant compared to steel.

• By using closed FRP profiles, hollow parts for weight reduction can be constructed easily. Light constructions with big static height provide benefits for wide spanned constructions, since UHPC´s elastic modulus is rather low compared to its compression strength.

• The flexible fabrication of varying FRP cross-sections and the free formability of UHPC allow the construction of customized and statically optimized structures.

• The joining of FRP components is rather problematic because of its low strength normal to fiber direction. By the combining FRP with UHPC, new alternatives for the introduction of single loads become possible.

4 BUILDING APPLICATIONS

In the following chapter, different building applications are investigated, which seem to be particularly appropriate for UHPC-FRP composite constructions. Up to now, UHPC applications in architecture are rather rare and limited to columns, pre-stressed constructions and non-load bearing façade applications without considerable tensile stresses. By the approach of reinforcing UHPC with FRP, new opportunities in design are provided, and the high performance of both materials is better utilized. The presented building applications (Figure 2-5) were designed in creative seminars with architecture students of the University of Technology, Graz (TU Graz, 2011) (TU Graz, 2012).

4.1 *Free Formed Shell Constructions*

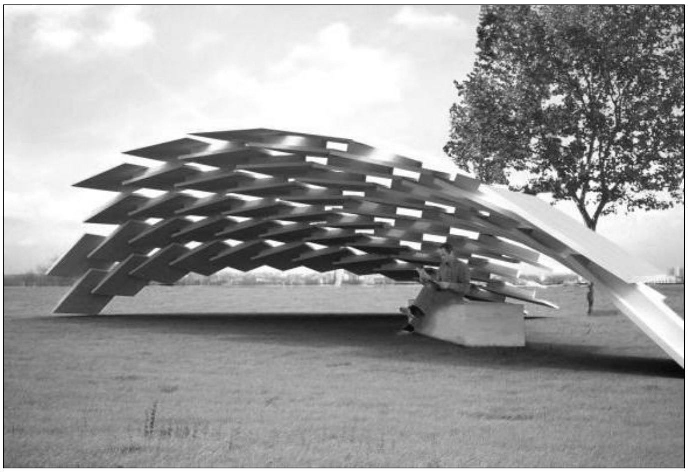

Figure 2. Prefabricated UHPC shell construction – student work by Florian Hackl, Martin Rieger and Stefan Schöttl (TU Graz, 2012).

Free formed shell constructions appear frequently in contemporary architecture and are usually constructed with steel grids. Prefabricated thin UHPC elements could represent an interesting alternative, since the material can be poured into almost any form without energy intensive processes. Centric reinforcement made of CFRP-lamellae increases the load capacity without enlarging the material thickness and can be bent into curved formwork easily due to its low bending stiffness. Furthermore, centric CFRP reinforcement might be able to reduce or completely substitute the UHPC´s steel fibers, whose alignment is difficult to control.

Figure 3. Prefabricated UHPC shell construction – student work by Stephanie Jordan, Nikolaus Pfusterschmied and Felix Zmölnig (TU Graz, 2012).

4.2 *Slim/Light Prefabricated Concrete Elements*

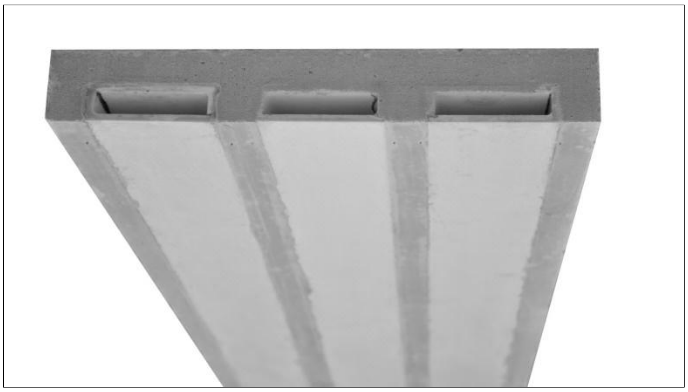

Figure 4. Light weight floor element made of UHPC and GFRP tube elements – student work by Magdalena Lang and Romana Streitwieser (TU Graz, 2011).

Uniaxial spanned elements made of UHPC and GFRP-profiles are another promising application. The GFRP functions as reinforcement and lost formwork at the same time and enables the production of efficient and light structural elements. For the manufacturing of non-standardized GFRP cross sections, available profiles can be joined together with glue. The conglutination is relatively simple, since the adhesive gap runs parallel to fiber direction and solely transfers shear forces (see Figure 6).

The developed composite elements can be used for beam structures and columns as well. Compressive forces are absorbed by the UHPC shell, tension forces as a result of bending loads and buckling problems by the GFRP.

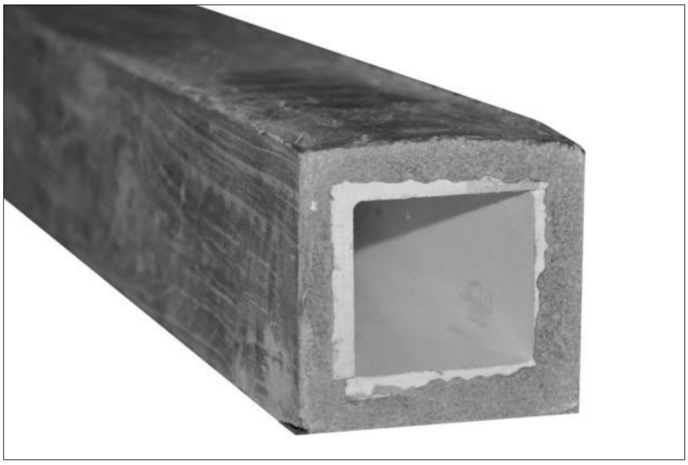

Figure 5. Quadratic hollow profile made of UHPC and GFRP tube elements – student work by Philipp Kramer and Mathias Schmid (TU Graz, 2011).

Figure 6. Fabrication of a GFRP tube profile by conglutination of two angles.

4.3 *Façade Application*

Another promising application of UHPC-FRP composites are light façade elements, which consist of thin UHPC plates and a thermally insulated core, as shown in Figure 7. By frictional connection of plates and insulation, sandwich elements with high degree of stiffness and stability can be realized. High quality concrete plates enable architecturally demanding surface design and coloration, the good thermal insulting properties of GFRP can be utilized to avoid heat bridges.

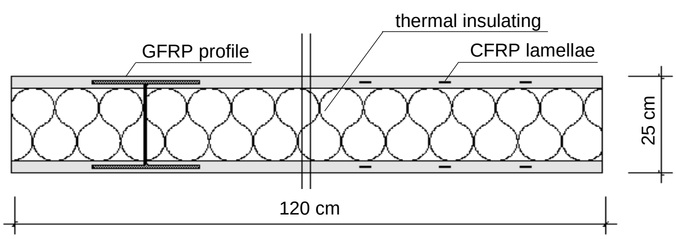

Figure 7. Concept of a thermally insulated UHPC sandwich element.

5 FEASIBILITY STUDY

For evaluation of the intended applications´ feasibility, a comprehensive research into the bond and bending behavior of UHPC-FRP composites was carried out. In the following, the results of a pull-out test series with UHPC and CFRP-lamellae, and the results of a bending test series using thin UHPC-plates with centric CFRP-lamellae are presented.

5.1 *Bond Behavior*

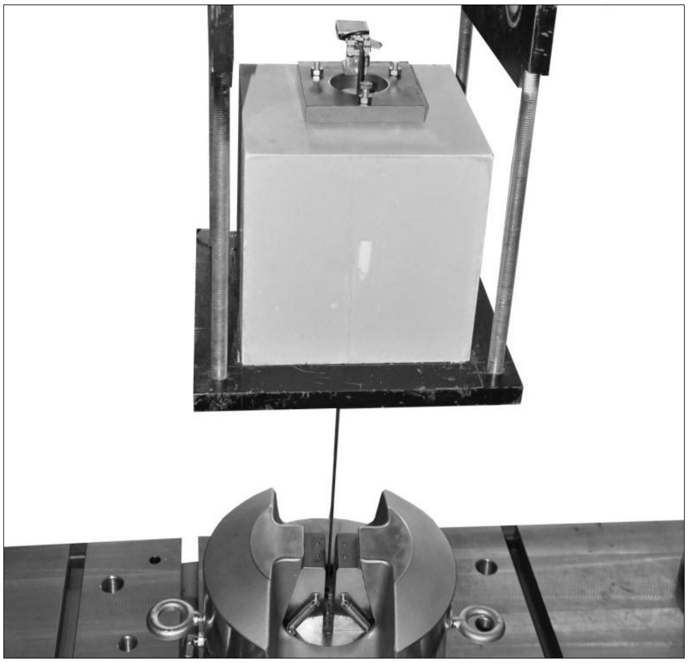

Figure 8. Experiment setup of the performed pull-out tests.

The described pull-out tests were carried out in October 2011 at the Laboratory for Structural Engineering at the University of Technology Graz (see Figure 8 and 9). The research target was to explore the bond behavior of UHPC and FRP in principle, and to find out the influences of surface roughening. The tests were carried in accordance to RILEM Recommendations (RILEM, 1982).

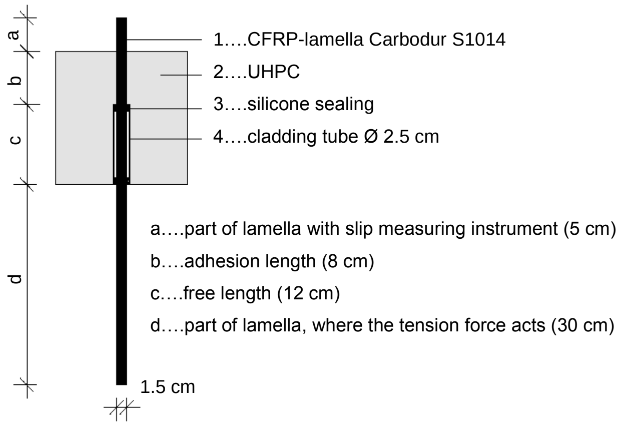

Figure 9. Experiment setup of the performed pull-out tests.

The concrete cubes had dimensions of 20x20x20 cm and were manufactured with Ceracem, a UHPC premix developed by the companies Sika and Eiffage, which has maximum aggregate grain size of 7.0 mm and a steel fiber content of 2.0 vol.-%. (Maeder, 2004). The test objects were stripped after 24 hours and stored in the laboratory for at least 28 days without water storage or thermal after treatment. The CFRP-lamellae Carbodur S1014 (mechanical properties: see Table 2) were used as reinforcement elements and were cut to cross sections of 15 mm x 1.4 mm.

The tests were carried out with three varyingly rough lamellae surfaces: smooth (test series 1), fine sanded (test series 2) and coarsely sanded (test series 3). The smooth lamellae did not have any after-treatment, whereas the surface of the fine and coarsely sanded lamellae was manually coated with Sikafloor-156, a 2-component epoxy resin, and covered with quartz sand, which had maximal grain size of 0.8 mm. The fine sanded variant had an approximate resin thickness of 0.1 mm and the surface was only partially covered with sand grains. The coarsely sanded lamellae had an approximate resin thickness of 0.4 mm and the surface was fully covered with sand grains (see figure 10).

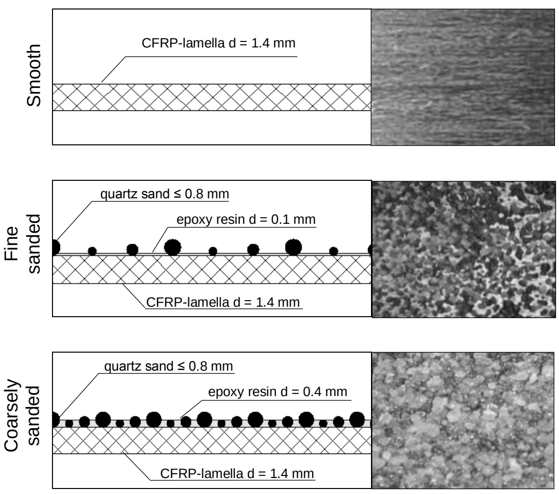

Figure 10. Investigated different types of surface characteristics.

Figure 11 and Table 3 show that fine sanded surface (test series 1) achieved the best bond strength results by far with an average maximum bond stress of 8.30 N/mm². The smooth and coarsely sanded surface achieved an average of 2.51 N/mm² (test series 1) and 1.99 N/mm² (test series 3), which demonstrates that the surface roughening does not necessarily lead to bond strength improvement. The coefficient of variation, a measure of results´ dispersion, was 0.32 for smooth, 0.08 for fine sanded and 0.27 for coarsely sanded surface. Consequently, the fine sanded lamellae also achieved the lowest dispersion.

The test series 1 with fine sanded lamellae reached a maximum pull-out force of approximately 20 kN with a bond length of 8 cm. On the assumption, that the maximum chargeable bond stress remains constant when the bond length is enlarged, the projected anchorage length of the investigated CFRP lamellae is 25 cm.

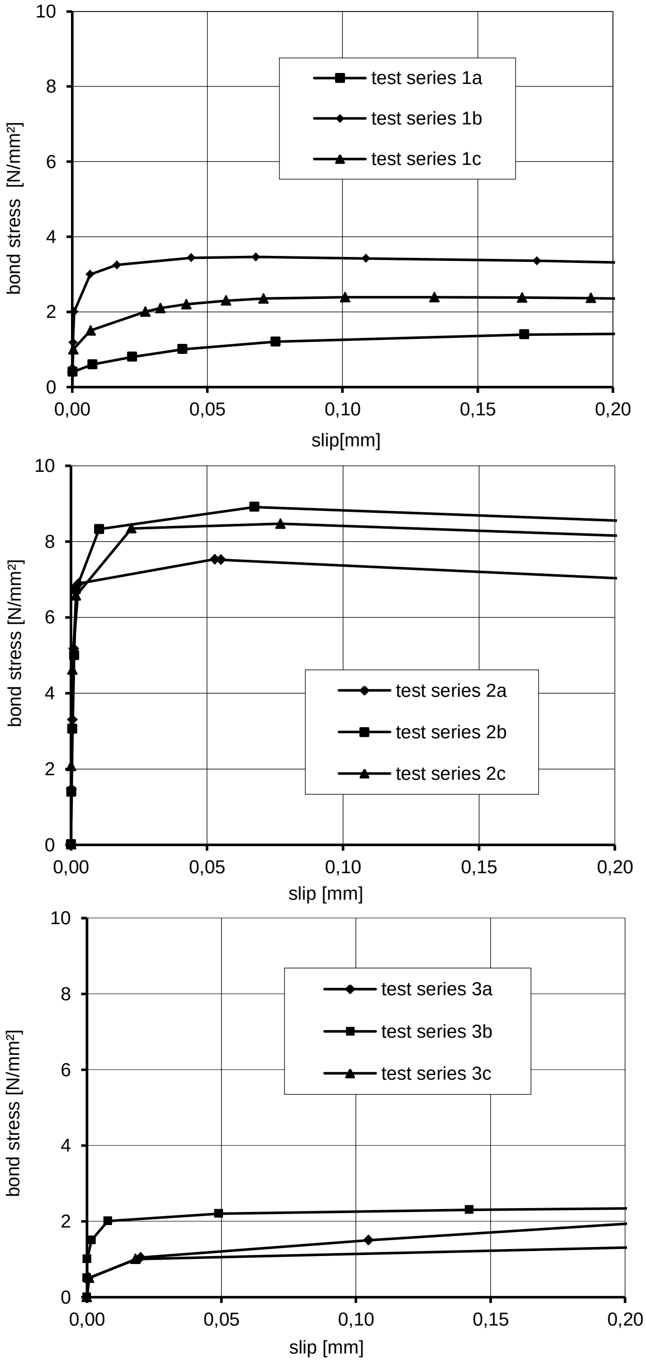

Figure 11. Bond stress-slip relationship of test series 1-3.

Table 3. Mean values and coefficients of variation (COV) of maximum bond stress and corresponding slip.

Characteristic values	test series 1	test series 2	test series 3
Number of tests	3	3	3
Maximum bond stress	2.51	8.30	1.99
COV	0.32	0.08	0.27
Corresponding slip (mm)	0.08	0.04	0.27
COV	1.35	0.12	0.35

5.2 *Bending Behavior*

For the investigation of basic bending behavior of thin walled UHPC-plates with steel-fibers and centric CFRP-lamellae, 4-point bending tests were carried out in February 2012 at the Laboratory for

Structural Engineering (see Figure 12-14). The plate elements had a thickness of 2.5 cm and spanned a length of 60 cm. The CFRP surface was roughened with fine sand, as described chapter 5.1.

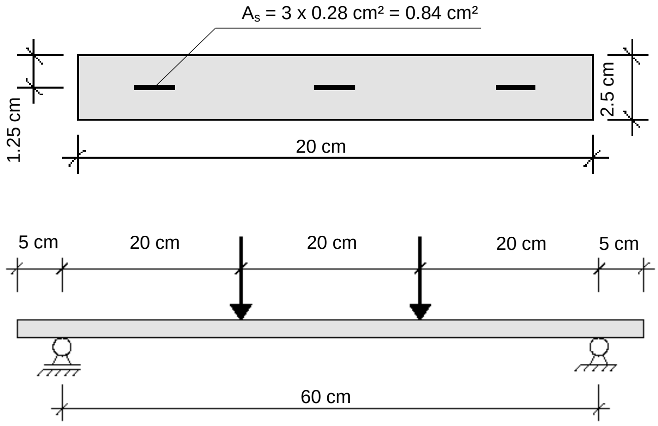

Figure 12. Top: Cross section of the UHPC plate used for test series 1; Bottom: Experiment setup for the 4-point bending test.

In order to get comparison values, the tests were carried out with two different types of reinforcement: UHPC plates with steel fibers and 3 centric CFRP-lamellae (test series 1), and UHPC plates with steel fiber reinforcement only (test series 2) as shown in Figure 13. The test´s intention was to investigate the influence of centric CFRP-reinforcement on stiffness, crack formation and maximum load capacity of thin UHPC plates.

Figure 13. UHPC plates with and without centric CFRP lamellae (test series 1 and 2).

The used UHPC had a maximum aggregate grain size of 5.0 mm, 1.0 vol.-% steel fiber content and a water/cement-ratio of 0.285. The target compression strength was 160 N/mm². The plates were stripped after 24 hours and stored in the laboratory for at least 28 days without water storage or thermal after treatment.

Fig. 15 and Table 4 show that UHPC plates with centric CFRP reinforcement (test series 1) had an almost 8 times higher breaking load than those without (test series2). Consequently, the reinforcement causes a significant increase of load bearing capacity. The bending stiffness EJ^{I} in the non-cracked condition was 150000 (test series 1) and 120000 kNcm² (test series 2), the concrete cracked at a moment of 35 kNcm (test series 1) and 31 kNcm (test series 2). Thus, the centric CFRP reinforcement did not increase bending stiffness in non-cracked condition and crack moment substantially.

Figure 14. Test series 1 shortly before reaching breaking load.

The bending stiffness in the cracked conditions EJ^{II} was 41000 kNcm², which is approximately 27% of the bending stiffness in the non-cracked condition. The theoretically determined bending stiffness in the cracked condition without taking into account tension stiffening effect and fiber reinforcement is 12000 kNcm², which is 3.4 times lower than the experimentally determined value. Hence, the good bond properties between CFRP and UHPC and the steel fiber reinforcement do have a remarkable influence on bending stiffness of the investigated plate.

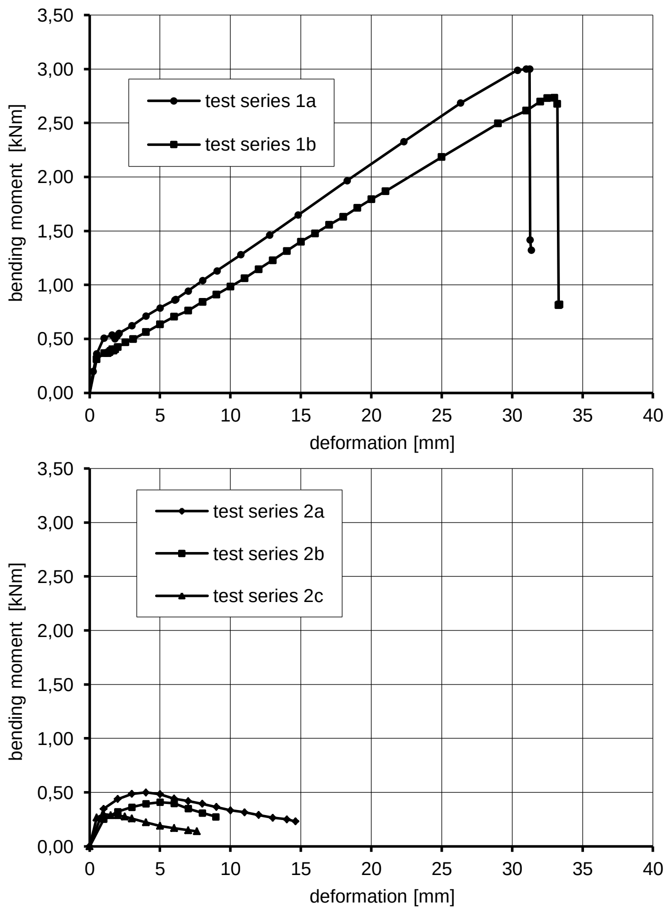

Figure 15. Bending moment-deformation relationship of test series 1 and 2.

Table 4. Mechanical properties of investigated plate elements.

Characteristic values	test series 1	test series 2
Number of tests	2	3
Max. bending moment	287 kNcm	40 kNcm
Crack moment	35 kNcm	31 kNcm
Bending stiffness EJ^{I}	150 000 kNcm^2	120 000 kNcm^2
Bending stiffness EJ^{II}	41 000 kNcm^2	-
Average crack distance	3.0 cm	-

In test series 1, the average crack distance on the underside of the plate was approximately 3.0 cm. This value also confirms the good bond properties, which were described in chapter 5.1. In test series 2, only one single crack appeared after exceeding the concrete´s tensile strength, which kept on growing with increasing load (see Figure 16).

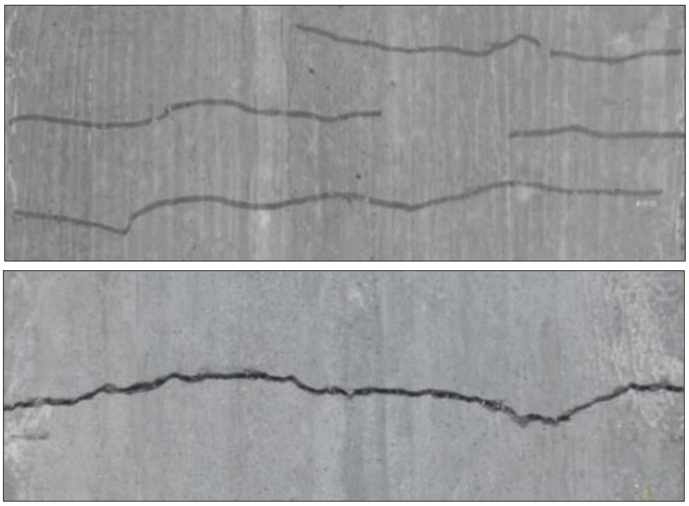

Figure 16. Crack pattern on the underside of the plate. Top: Steel fiber reinforced UHPC plates with CFRP-lamella; Bottom: Steel fiber reinforced UHPC plates without CFRP-lamella.

6 CONCLUSION

Structures made of UHPC and FRP are a new kind of composites, which have only rarely been investigated up to now. Both materials are characterized by high mechanical and environmental resistance, and the good adhesion properties of UHPC make the combination with FRP reasonable.

The investigated construction method could be applied successfully to thin walled UHPC structures with CFRP lamellae for reinforcement. Due to the easy formability of UHPC, the construction of geometrically complex structures with prefabricated elements should be thought about. Furthermore, the combination of UHPC with structural GFRP profiles could generate light and robust alternatives to steel and timber constructions. Another interesting aspect is the utilization of GFRP´s low thermal conductivity and the creation of thermally insulated elements for façade applications.

For evaluation of feasibility, pull-out tests with CFRP lamellae and UHPC were carried out, which show similar results as with normal concrete and circular FRP rods described in literature (Cosenza, 1997). Proper sanding of the outer surface of FRP causes a remarkable increase of bond strength due to better chemical adhesion and friction coefficient. The pull-out tests achieved bond stress values up to 8.30 N/mm², which is more than two times higher than those of steel reinforcement and normal concrete C25/30 (4.05 N/mm²) according to EN 1992-1-1. However, the increases in bond strength are related to an increase of brittleness.

For investigation of flexural behavior, 4-point bending tests were carried out. The results show an enormous increase of bending load capacity due to centric CFRP reinforcement and a linear elastic behavior until material failure. The results correspond with the behavior of over-reinforced cross sections in accordance to ACI 440.1R-06 (2006), where the material failure is characterized by concrete crushing.

Both performed studies suggest that a technical feasibility is given, although further extensive experimental and analytical investigations are required.

7 ACKNOWLEDGEMENT

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