Supporting Structures made of UHPC

UHPC seminars with architecture students at the Technical University of Graz

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Introduction

The Institute for Structural Design, situated at the University of Technology, Graz, organized a seminar and student competition with title "Supporting Structures made of UHPC" in the winter semester 2010/11, where the basic design principles of ultra-high performance concrete (UHPC) were taught to architecture students. The lecture took place in cooperation with Prof. Nguyen Tue, head of the Institute for Structure Concrete, Dr. Bernhard Freytag, head of the Laboratory for Structural Engineering, and was kindly supported by the company Max Boegl from Sengenthal, Germany, who enabled the competition.

Competition Tasks

The company Max Boegl plans the construction of a roof structure for bulk materials, which emerge during the production and recycling of asphalt and concrete. The modular precast UHPC construction should be customizable, portable and easy to assemble and disassemble in order to allow temporary use on different sites. Furthermore, the modules should have a large number of identical parts to realize effective and economical serial production and reduce costs for quality monitoring, since UHPC is mostly monitored by destructive methods.

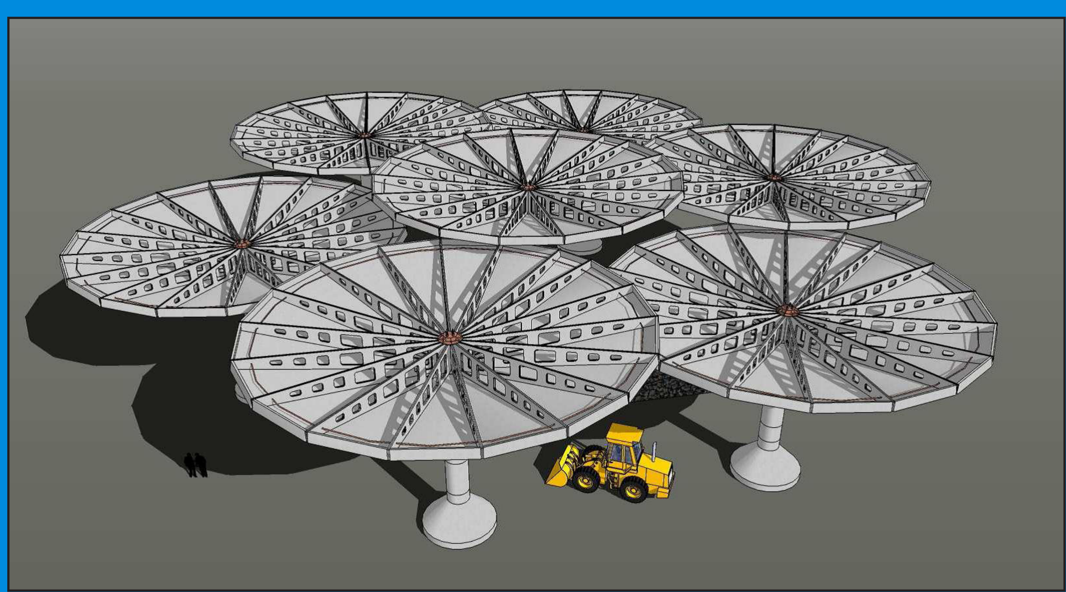
Conclusion

The main aim of the lecture and student competition was the finding of efficient and material-appropriate supporting structures for the relatively young material UHPC. According to the competition tasks, the architecture students designed a large number of different types of structures like arches, folded plates or frames. Since there are only a few UHPC reference projects yet, the competition was focused on finding creative and innovative solutions to the following problems:

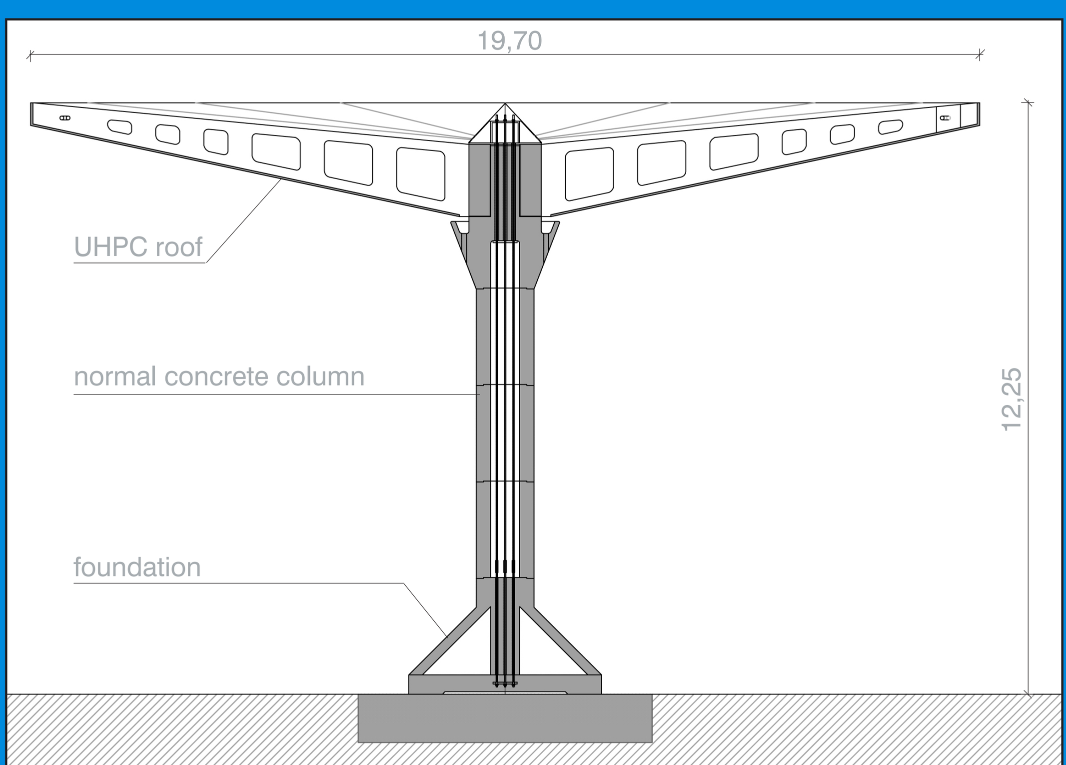
- utilization of the high compressive strength of UHPC,
- handling with the low tensile strength of UHPC and
- joining of the precast modules.

"Giant Parasol"

Christian Weissensteiner, Richard Rollett

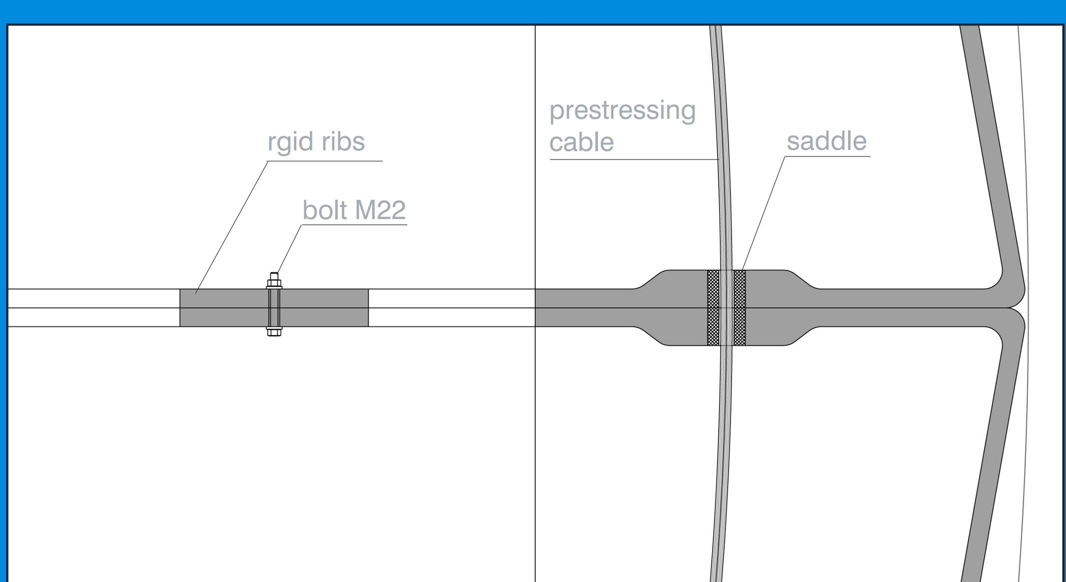


The basic element is a concrete parasol, which allows flexible design of the roof structure and has of a large number of identical elements. The parasol consists of a massive column made of normal concrete, which can resist the crash of a truck without damage, and a light circular roof made of UHPC. Since the roofs are vertically offset, sun light can enter and exhaust gases can escape easily.



standard section structure

The normal concret column is approximately 10 m high and has a diameter of 1,0 m. It has a wall thickness of 30 cm and is subdivided into 2,0 m long elements for easy transportation. The UHPC roof has a diameter of 20 m and is subdivided into 18 elements. The circular plate has a thickness of 3,0 cm and is stiffened with ribs, which have a height of 1,50 m in the center and 0,50 m at the outer edges. The ribs have quadratic slots to reduce own weight and the roof is pre-stressed with a circular running cable. Since the roof is made of transportable and mostly identic elements, it can be assembled easily on site. The roof elements are bolt together and pre-stressed on the ground. After raising it onto the column, the whole parasol is vertically pre-stressed to prevent tensile forces.

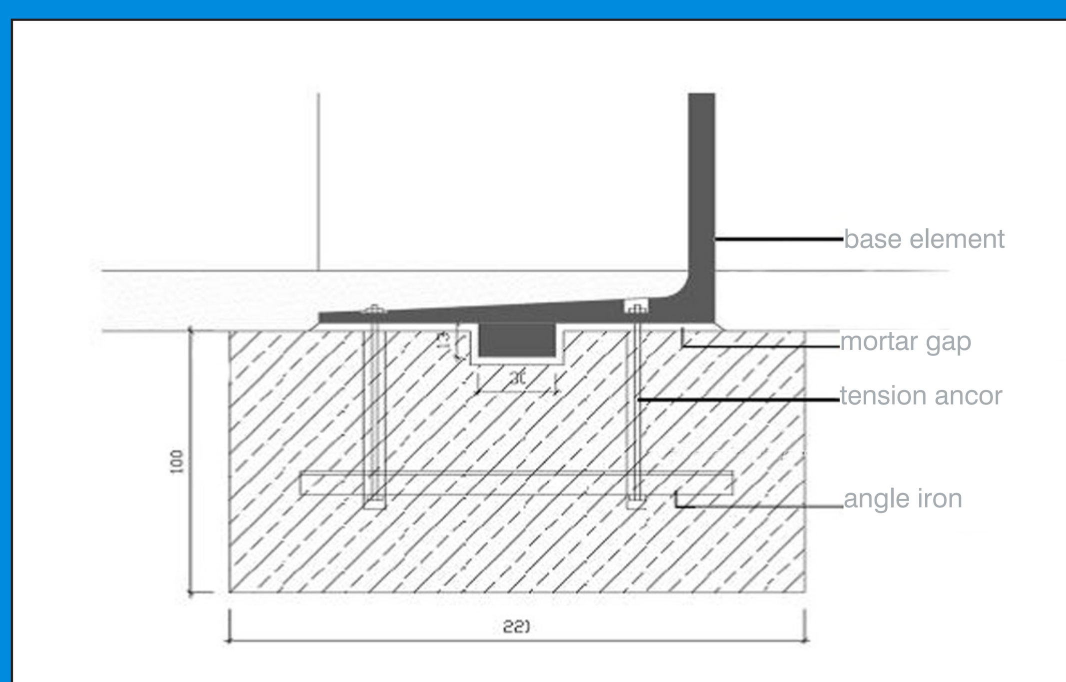


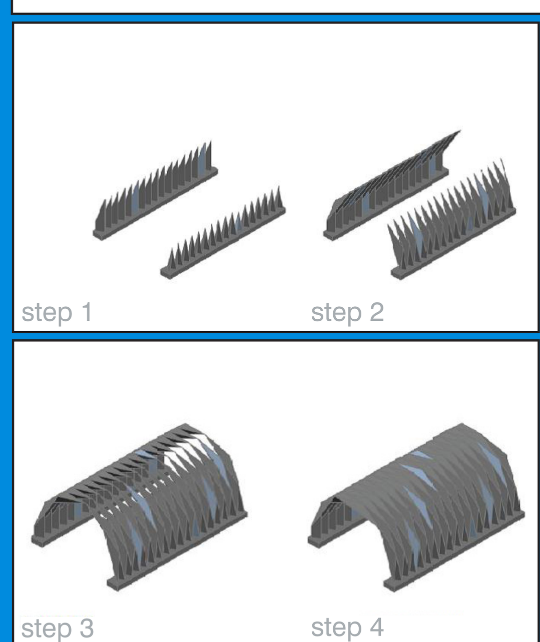
detail: connection of elements

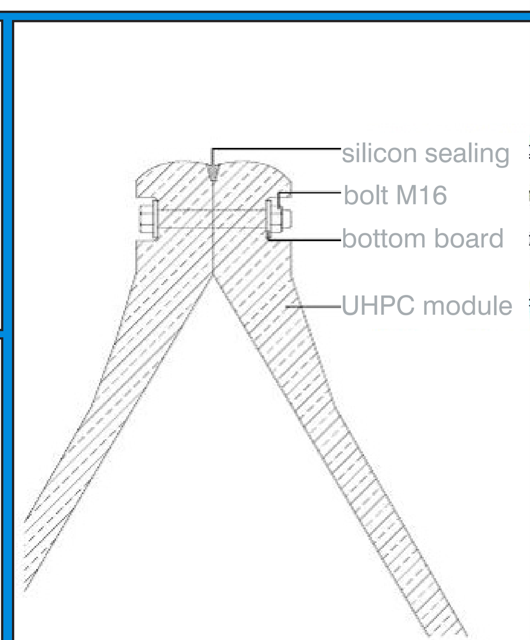
"Mobile Folding"

Alexia Eberl, Angelika Krainer, Catharina Maul

The roof structure has the shape of an arch (span width = 20 m) and is realized with spatially folded plates made of precast UHPC. The arch represents a very effective supporting structure since evenly distributed symmetric loads mainly produce compression forces. Bending moments, which result from single and asymmetric loads, can also be transferred by the structure easily, since the folded plates have a static height of 1,60 m.



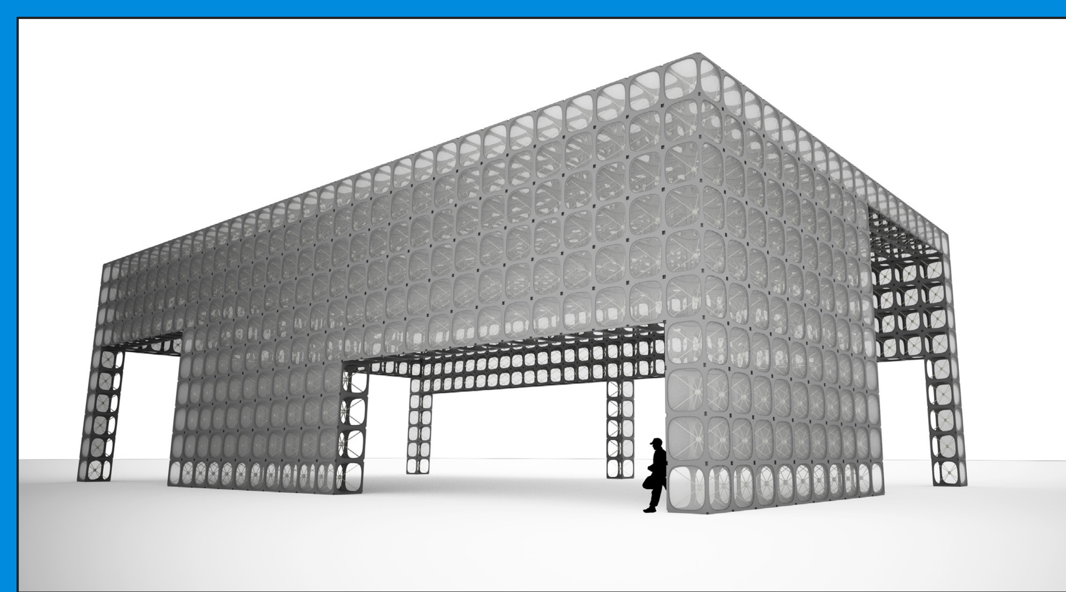




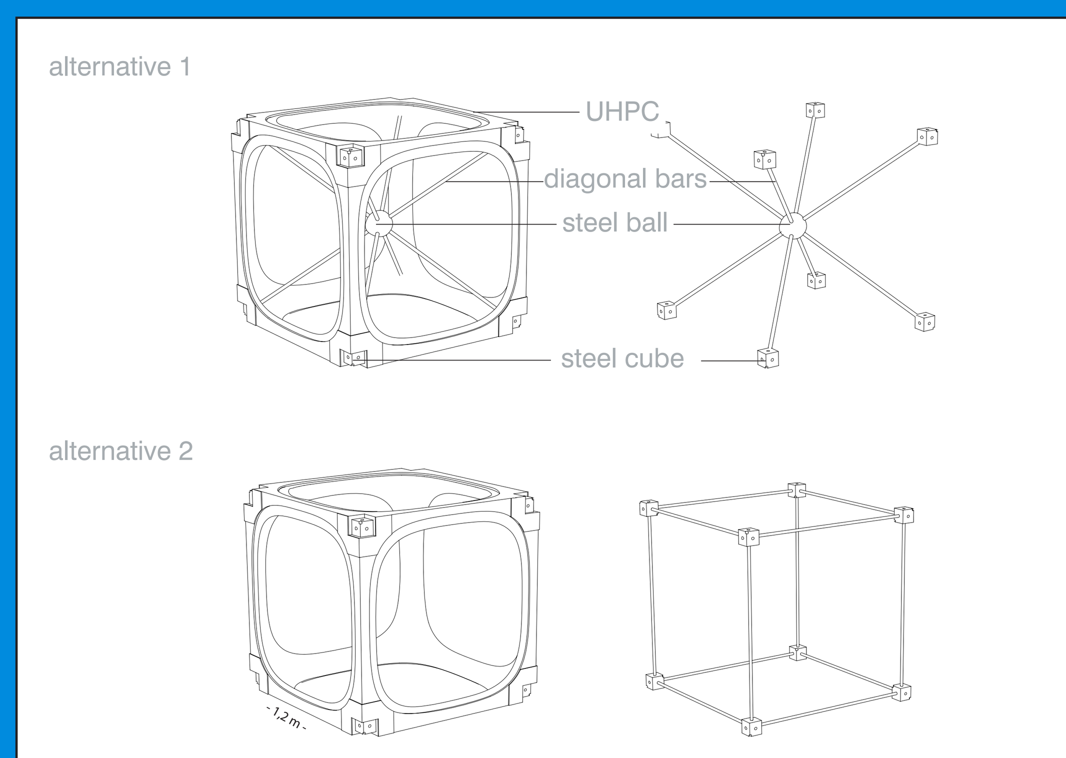
The connection of two folded plates is realized with pre-stressed steel bolts, which press the contact surfaces together and activate friction forces in the gap. Initial calculations showed that the structure possesses high rigidity for low own weight. Since the occurring forces do not exceed the tensile strength of UHPC, no conventional reinforcement or pre-stressing is necessary. The calculation also showed that single elements can be removed easily so that daylight can enter the roof structure. Furthermore, the high rigidity allows the assembling of the structure without scaffolding

"Pixelwork"

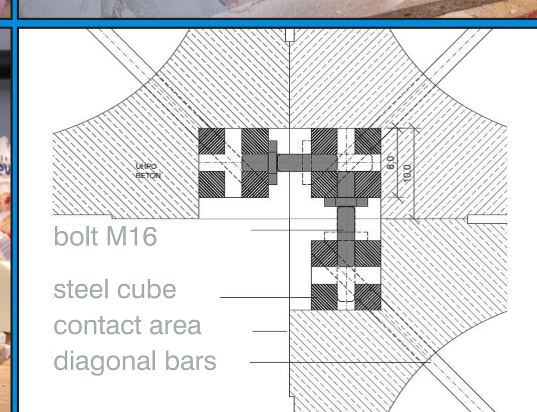
Thomas Bauer, Philipp Kramer



The idea behind this project is the realization of a roof structure with only one single element (pixel), which can be added to columns, beams, walls or ceilings and allows maximum flexibility. This idea was implemented by a hollowed UHPC cube measuring 1,20 m, which allows the design of a 20 m spanned and 10 m high structure.



The static system of the roof structure is a rigid frame and bending stresses are mainly transferred by a couple of tensile and compression forces in the upper and lower belt. For reinforcement steel bars are integrated into the UHPC beams and / or diagonal bars stiffen and pre-stress the elements. The joining of the elements is only done by screwing; pre-stressing cables are not applied. The UHPC-body is produced in one pour and has a simple and re-usable formwork.



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3rd International Symposium on Ultra-High Performance Concrete and Nanotechnology for High Performance Construction Materials

MAX BÖGL
Fortschritt baut man aus Ideen.

INSTITUT FÜR TRAGWERKSENTWURF

TU Graz
Graz University of Technology

Composites made of UHPC & GFRP

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Motivation

The ambition of this seminar was the design and development of innovative composite structures made of steel fiber reinforced Ultra-High Performance Concrete (UHPC) and Glass-Fiber Reinforced Polymers (GFRP). The material combination appears useful for several reasons: By combining UHPC and GFRP, efficient composite structures with a balanced ration between compressive and tensile strength can be created and the high resistance of both materials can be utilized. The compact UHPC protects the GFRP-components against harmful environmental influences and improves the fire resistance. By using closed GFRP profiles, hollow parts for weight reduction can be realized easily. Light constructions with big static height provide benefits for wide spanned constructions, since UHPC´s elastic modulus is rather low.

Realization

During the seminar, the architecture students designed innovative beam structures consisting of GFRP pultrusion profiles and UHPC. In addition, they tested the feasibility of their concepts by producing structural elements in real size. The manufacturing was kindly supported by Dr. Bernhard Freytag, head of the Laboratory for Structural Engineering, and the company "Exel Composites" from Kapfenberg. In order to archive high utilization of UHPC´s enormous compressive strength, the concrete wall thickness was reduced to a minimum, which required the use of fine grained UHPC and short steel fibers. The contact area between UHPC and GFRP was roughened with quartz sand in order to improve the bond characteristics. For the manufacturing of non-standardized GFRP cross sections, available profiles were joined together with epoxy based glue.

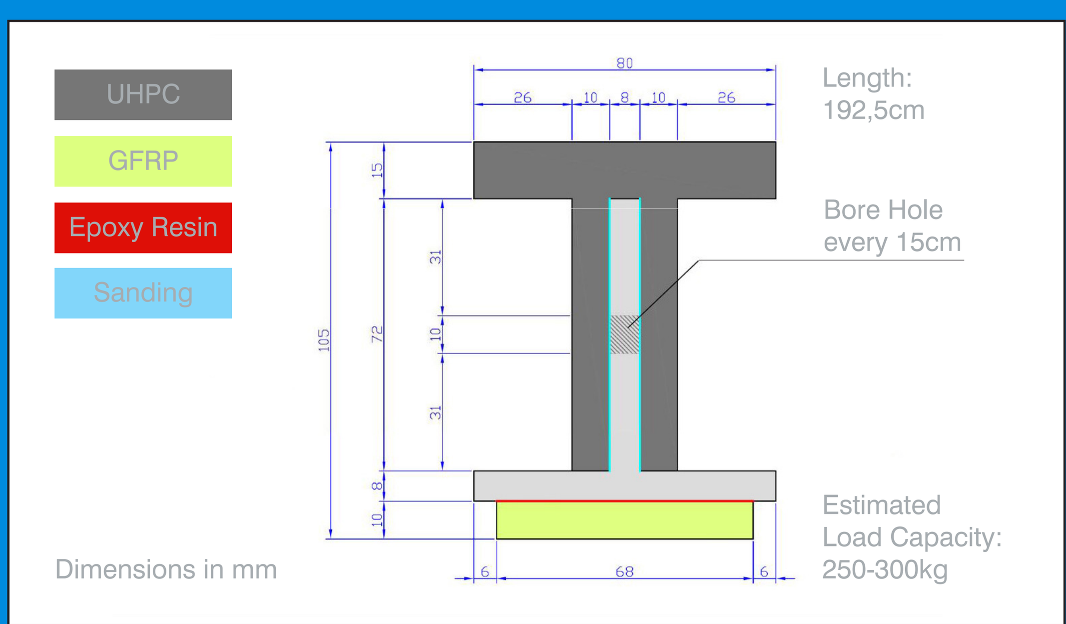
Conclusion

The manufactured prototypes give cause to believe that UHPC-GFRP composite beams could be a robust and lightweight alternative to steel profiles, timber girders and prefabricated normal concrete beams. The good thermal insulting properties make the use of GFRP also interesting for ceiling constructions and façade plates. The profiles are simply encased in concrete and work as lost formwork and tensile reinforcement at the same time. No additional reinforcement is required and the UHPC´s steel fiber content can be reduced to a minimum. Furthermore, hollow tubes make it easy to pre-stress the construction.

"Double-T Profile "

Markus Meirhofer, Bernhard Wagner

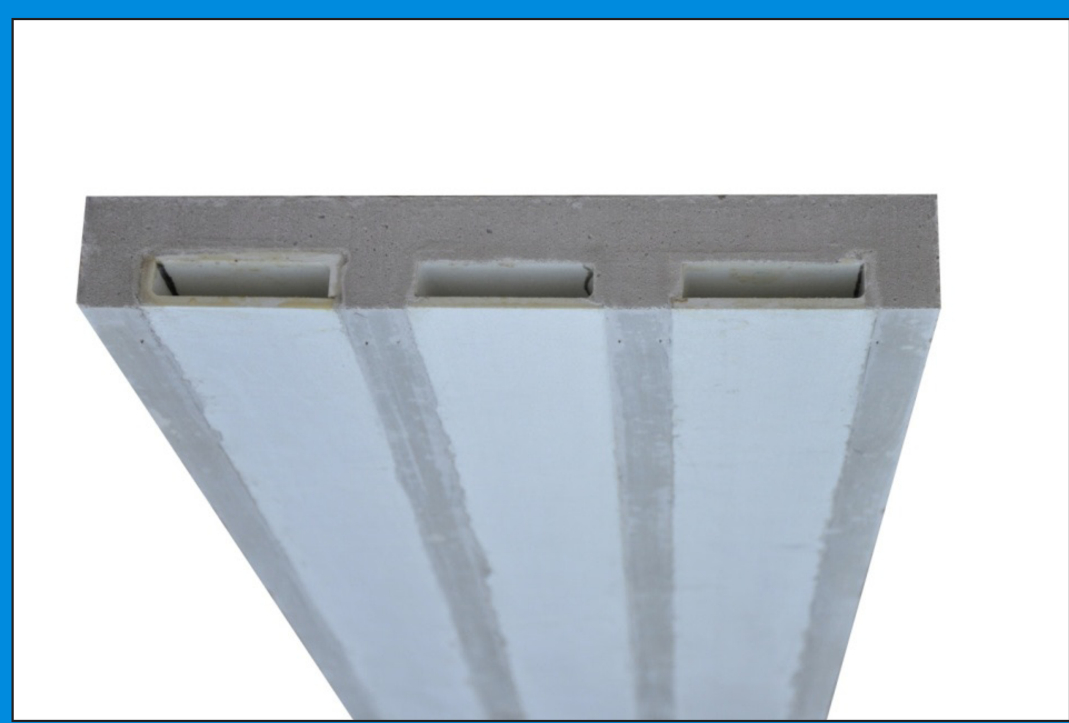
This group decided to develop a double-t profile, which represents a very efficient and material saving cross section for bending loads. It is designed for a single span beam with compression in the upper chord (material: UHPC) and tension in the lower chord. The web is mainly stressed by shear forces and consists of a GFRP-lamella, which is surrounded by thin UHPC walls.



Good bond properties are realized by sanding the GFRP surface and boring holes in the GFRP profile . The beam was designed to span a length of approx. 2, 5 m and is a light and corrosion resistant. The load bearing capacity is comparable with a steel profile HEA 100.

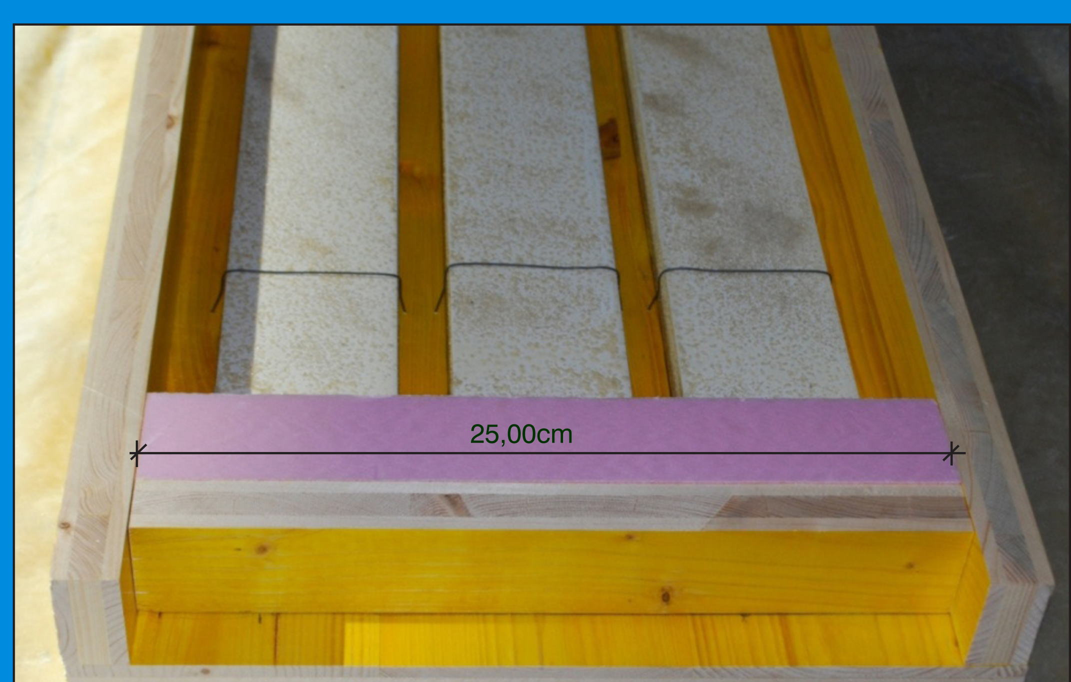
"Uniaxial Spanned Plate Element "

Magdalena Lang, Ramona Streitwieser



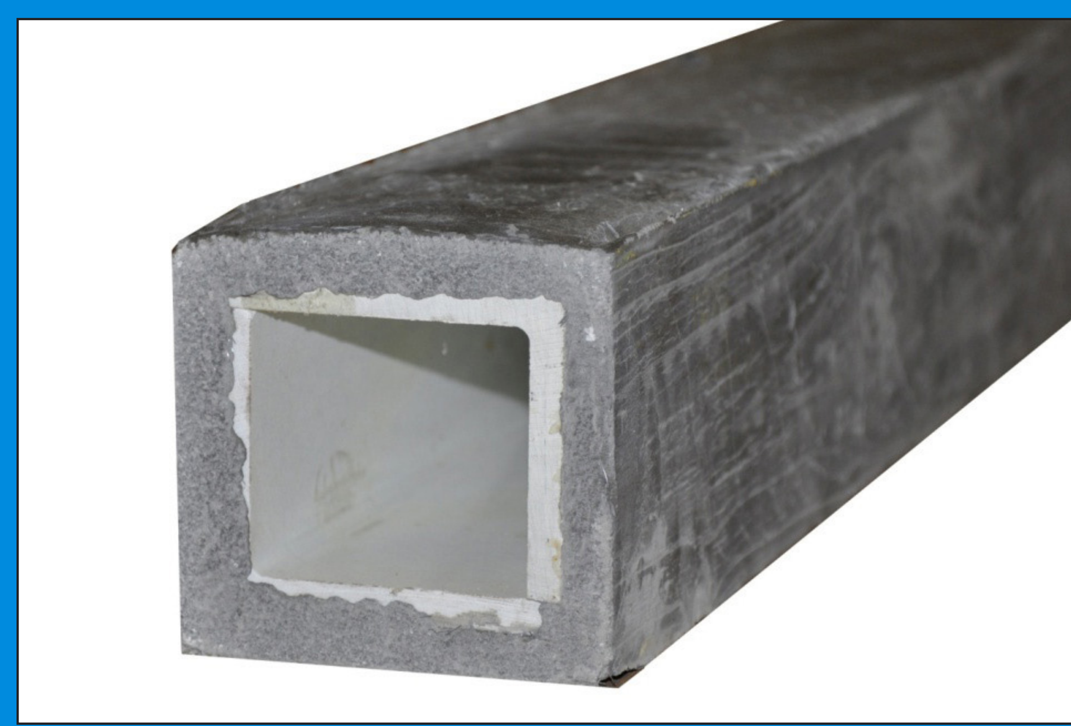
The developed composite structure is a plate element (thickness = 5,0 cm), which consists of UHPC and rectangular GFRP tubes. The tubes are produced by adhering standardized L-shaped profiles with epoxy based glue. Due to the continuous openings in the ceiling, the construction can be prestressed easily, which increases stiffness and load capacity.

The plate element could find application in wide spanned ceilings, where a high stiffness and low weight is needed, or façade plates, which take advantage of the good thermal insulating properties of GFRP.

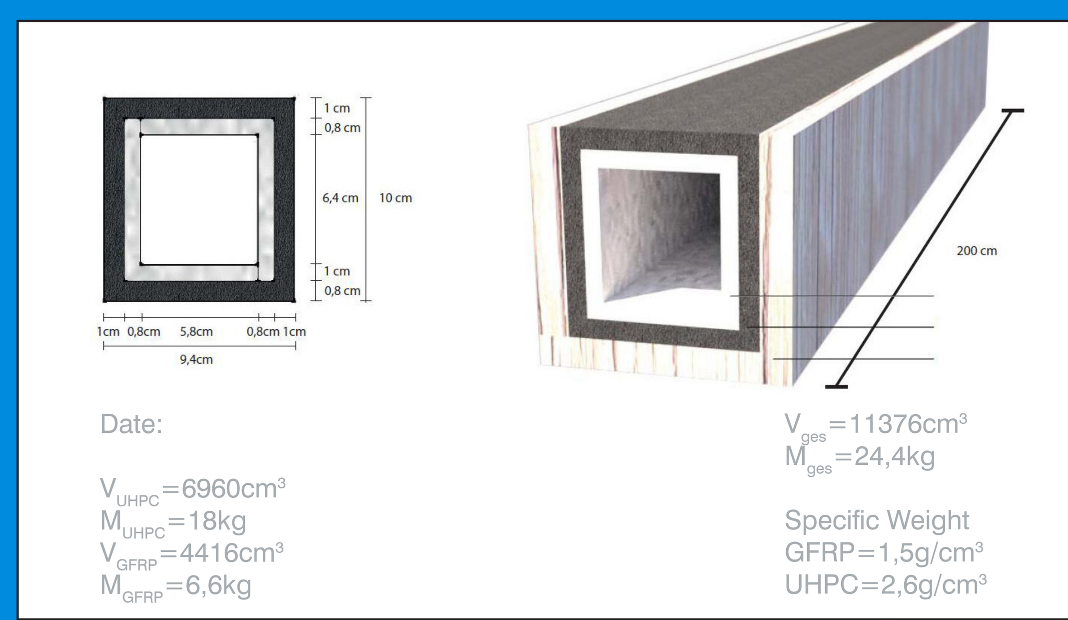


"Quadratic Hollow Profile "

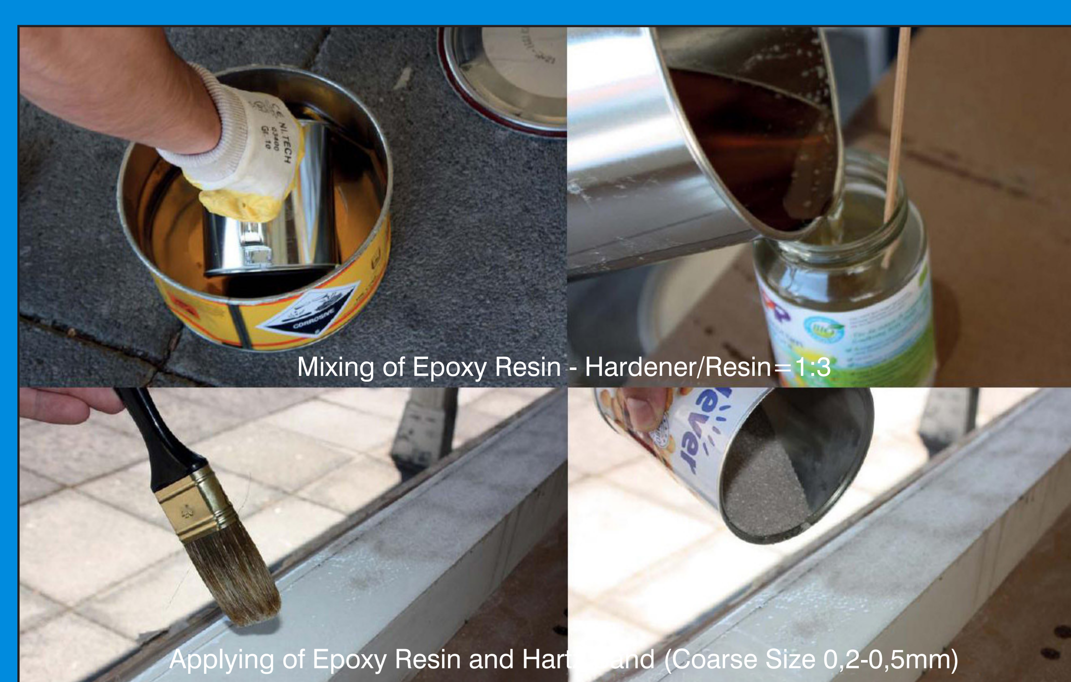
Philipp Kramer, Mathias Schmid



The aim of this group was the design of hollow profiles made of UHPC and GFRP, which can be used as beams and columns as well. The dense UHPC forms the outer shell and protects the GFRP against environmental influences and fire. Compression forces are absorbed by the UHPC shell, tension forces as a result of bending loads and buckling problems are absorbed by the GFRP.



The GFRP profile functions as reinforcement and lost formwork at the same time. This principle enables the production of efficient and light structural elements. Shear forces between UHPC and GFRP are solely transferred by bond forces, which emerge during the hardening of the concrete. The developed element spans a length of 2,5 m and can be compared with a steel profile 100x100x5 mm.



Mixing of Epoxy Resin - Hardener/Resin=1:3

Applying of Epoxy Resin and Har[illegible]and (Coarse Size 0,2-0,5mm)

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Slim UHPC-Plates with CFRP-Rebars

Research Work at the Technical University of Graz

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Ambition

The ambition of this study is the development of slim plate elements made of steel-fiber reinforced Ultra-High Performance Concrete (UHPC) and reinforcement consisting of Carbonfiber-Reinforced Polymer (CFRP) lamellae. The new generated construction method is characterized by low self-weight, high durability and simplicity, and could represent a corrosion resistant alternative to steel structures. The enormous compressive strength and the excellent bond properties of UHPC allow the design of extremely slim and filigree structures, as well as the use of high strength reinforcement like CFRP lamellae. For evaluation of feasibility, a comprehensive theoretical and experimental research into the bond and bending behavior of UHPC-CFRP composites is carried out and structural building applications like beams, shells and façade elements are investigated.

Problem Definiton

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 four ways to deal with this problem: reinforcing the tensile stressed areas, prestressing the construction, choosing a construction with low bending stresses or improving concrete´s tensile strength by using special types of cement. In this study, the first approach is followed by reinforcing slim UHPC plates with high-strength CFRP lamellae, which are positioned in the center of the cross section. This way of reinforcing is technically simple and does not have a strong influence on the structure´s form. Furthermore, the plate has a balanced flexural behavior under positive and negative bending moment and the plate thickness does not increase.

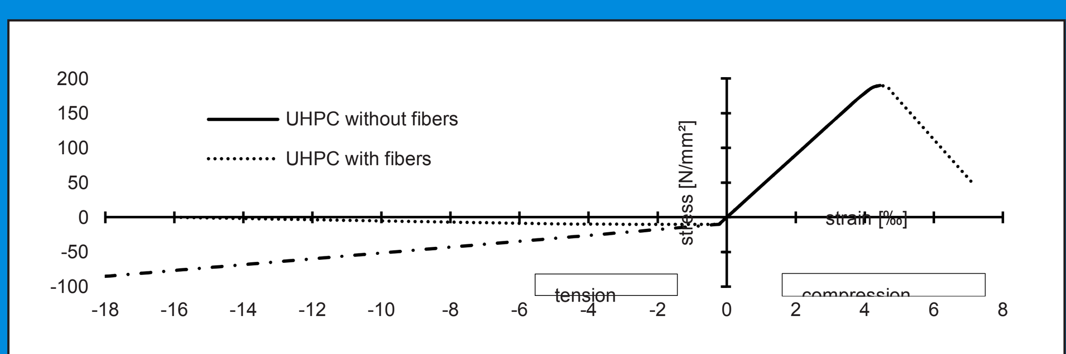
Conclusion

Due to its formability, the realization of geometrically complex structures with prefabricated elements are a promising application of thin UHPC plate elements. For evaluation of bond properties, pull-out tests with sanded CFRP lamellae and UHPC were carried out, which show similar results as with normal concrete and circular FRP rods described in literature. Proper sanding of the outer surface causes a remarkable increase of bond strength due to better chemical adhesion and friction coefficient.
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. However, the bending the bending stiffness and crack moment do not increase substantially by adding CFRP reinforcement.

Building Applications

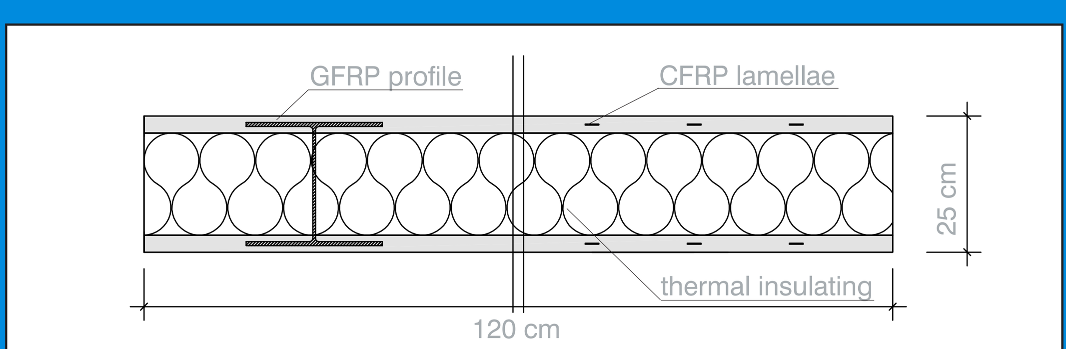
UHPC learning pavilion at the campus of the TU Graz – student work by Stephanie Jordan, Nikolaus Pfusterschmied and Felix Zmölnig

Up to now, UHPC applications in architecture are rather rare and limited to columns, prestressed constructions and non-load bearing façade applications without considerable tensile stresses. By the approach of reinforcing UHPC with CFRP, new opportunities in design are provided, and the high performance of both materials is better utilized.
Free formed shell constructions appear frequently in contemporary architecture and are usually realized 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 re-



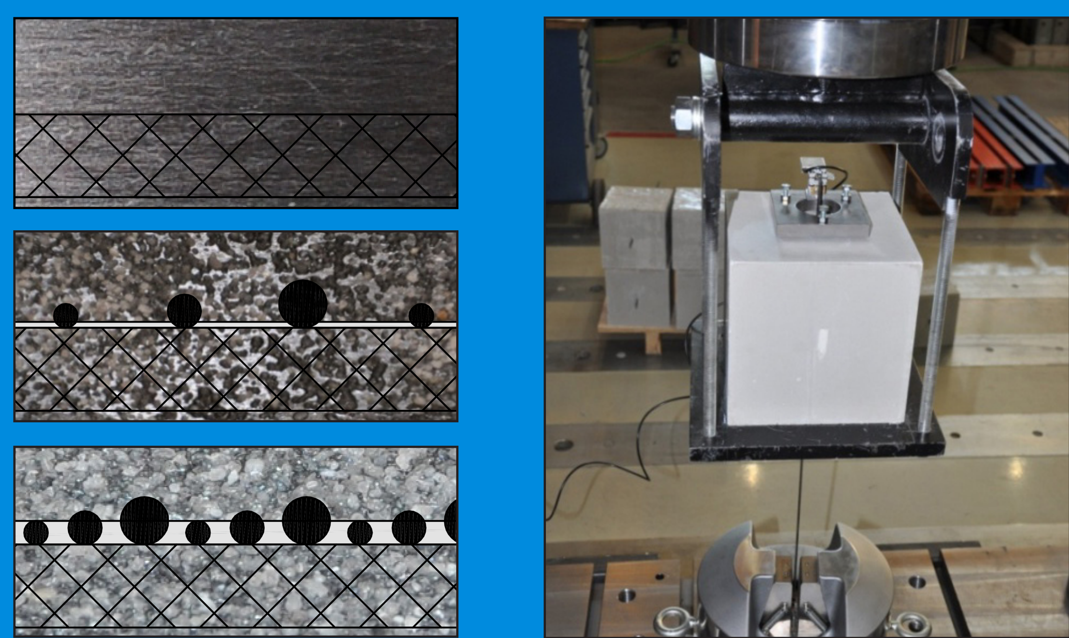
Qualitative stress-strain relationship of UHPC with different kinds of reinforcement under centric tensile and compressive load

inforcement 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.
Another promising application of UHPC-FRP composites are light façade elements, which consist of thin UHPC plates and a thermally insulated core. 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.



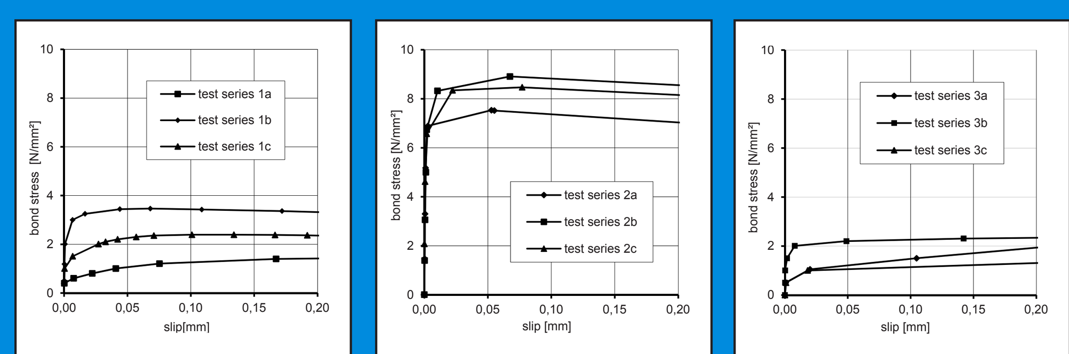
Concept of a thermally insulated UHPC sandwich element

Bond Bahavior



Investigated different types of surface characteristics & Experiment setup of the performed pull-out tests

For investigation of bond behavior of UHPC and CFRP-lamellae, pull-out tests were carried out in October 2011 at the Laboratory for Structural Engineering (TU Graz). The research target was to explore the bond behavior of UHPC and FRP in principle and to find out the influences of surface roughening of the CFRP-lamellae.
The concrete cubes were manufactured with Ceracem UHPC, which has maximum aggregate grain size of 7,0 mm and a steel fiber content of 2,0 vol.-%.



Bond stress-slip relationship of test series 1-3

The CFRP-lamellae Carbodur S1014 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 were manually coated with a epoxy resin and covered with quartz sand, which had maximal grain size of 0,8 mm.
The test showed that that fine sanded surface 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 and 1,99 N/mm², which demonstrates that the surface roughening does not necessarily lead to bond strength improvement.
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 re-mains constant when the bond length is enlarged, the projected anchorage length of the investigated CFRP lamellae is 25 cm.

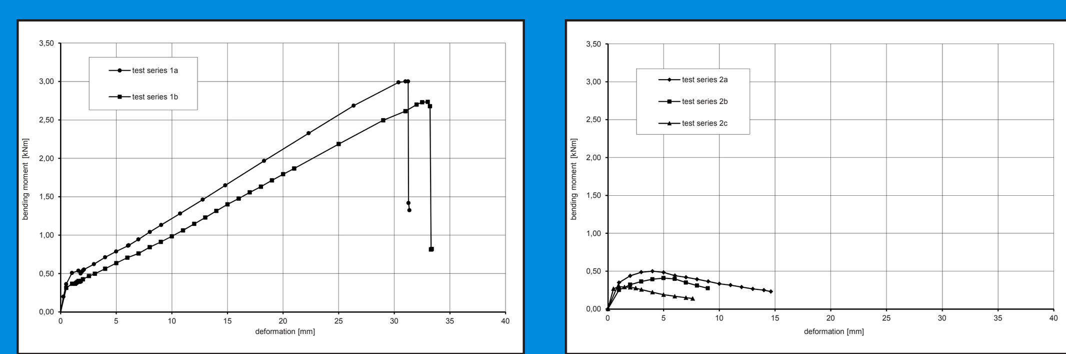
Type of outer surface -1	Number of tests -2	t_{max} (MPa) -3	COV -4	s_{max} (mm) -5	COV -6
Test series 1	3	2,51	0,32	0,08	1,35
Test series 2	3	8,3	0,08	0,04	0,12
Test series 3	3	1,99	0,27	0,27	0,35

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

Bending Bahavior

UHPC plates with and without centric CFRP lamellae ddddd and performed 4-point bending test

For the investigation of principle 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. 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. 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). The test´s intention was to investigate the influence of centric CFRP-reinforcement on



Bending moment-deformation relationship of test series 1 and 2

stiffness, crack formation and maximum load capacity of thin UHPC plates.

Fig. 11 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 series 2). Consequently, the reinforcement causes a significant increase of load bearing capacity. The bending stiffness EJI in the non-cracked condition was 150.000 (test series 1) and 120.000 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 in-crease bending stiffness in non-cracked condition and crack moment substantially.
The bending stiffness in the cracked conditions EJII was 41.000 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 account of tension stiffening effect and fiber rein-forcement is 12.000 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. 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 6.1. In test se-

Characteristic values	Test Series 1	Test series 2
Number of test	2	3
Max. bending moment	287 kNcm	40 kNcm
Crack moment	35 kNcm	31 kNcm
Bending stiffness EJ^{I}	150.000 kNcm²	120.000 kNcm²
Bending stiffness EJ^{II}	41.000 kNcm²	-
Mean crack spacing	3,0 cm	-

Mechanical properties of investigated plate

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