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From Jointing Systems to Light-Weight Structures: Hybrid, dry-fit beam, surface and spatial structures made of UHPFRC

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Abstract

Today structural design is mostly guided by cast-on site construction members, with simple linear formwork. Those load-bearing structures are mostly mass-intensive and inefficient in terms of material strength. Saving the “grey embodied” energy of those heavy members will be very important in the future. The developed construction method of the “digital workflow” for design and fabrication with CNC-milled formwork of non-standard joint structural members has shown its potential for spatial and shell structures in previous research projects as in Lehmberg *et al.* [1]. By combining the research of spatial and shell elements with non-metallic pre-stressing technology precast dry jointed structural members can be used to utilize the strength of the material efficiently. With the developed dry jointing systems a modular, efficient and cost effective coffered ceiling can be build (Figure 3) which will be capable by spatial nodes to create dome structures in the future (Figure 13). This ongoing research is part of the priority programme 1542 by the German Research Foundation (DFG) on digital fabrication for new jointing systems which has been extended to hybrid beam and slab structures.

Keywords: UHPFRC, modular, hybrid, T-beam, slab, non-standard jointing principles, lightweight construction, resource efficiency, digital workflow.

1. Introduction

Saving of energy will be key to new building systems. For this the jointing of high-precision casted ultra high performance fibre reinforced concrete (UHPFRC) will become efficient with their high durability and strength by lowering the mass and using shape optimized constructions. Without reinforcement the ultra thin building technique enables light weight modular construction which can be placed on site. Without reinforcement the need for pre-stressed systems is imminent. With compression only systems the bending strength of the material can be used more efficiently. For the ongoing research a UHPFRC with self levelling capabilities was used (Figure 1).

components	**mass [kg/m³]**
cement CEM I 52,5 R	595
silica fume	69
quartz flour I	314
quartz flour II	119
quartz sand	1029
steel fibres (l = 9 mm)	192
super plasticizer	40
water	156

Figure 1: Content of mixture FK1-2.5 fine grain UHPFRC.

The UHPFRC with high compressive and flexural strength is ideally suited to be used for thin structures because of its fine grain and self-levelling capabilities. Moreover these characteristics make it possible to cast modular and high precision members, which are connected by high precision casted joints without putty, built-in parts or any kind of finishing. Enabled by high precision prefabrication, members can be dry-jointed and hereby easily assembled on site. Every member of the system is mass optimized for its specific loads and structural purpose. Therefore, a "Digital Workflow" that consolidates parametric design, modularization, jointing and construction detailing as well as fabrication was developed. The developed structures are pre-stressed to make use of the high compressive and flexural strength of the UHPFRC (Figure 2).

material properties	**[MPa]**
young's modulus E_{cm}	46,700
compressive strength f_{ccm}	151
tensile strength f_{ctm}	10
flexural strength $f_{ctm,fl}$	15
poisson ratio ν	0.18 [-]

Figure 2: Material properties of mixture FK1-2.5 fine grain UHPFRC.

By making use of the Digital Workflow a modular pre-stressed lightweight structure with spatial and shell structural elements was developed (Figure 3). Research on shell and spatial elements already showed the potential of UHPFRC for lightweight construction (Lehmberg *et al.* [1] [2], Mainka *et al.* [3]). The aim of this research is to transfer the developed new jointing principles for UHPFRC components into more rigid lightweight hybrid beam, surface and spatial structures (Figure 13). The goal is to increase the load bearing capacity of structural components and systems by intelligent coupling of individual modular beam and shell elements into hybrid, cooperating supporting elements and systems. By combining dry fit pipe / bar members associated with shear resistant, flat or curved surface elements, a variety of relevant building structure types like coffered ceilings (Figure 3) can be realized. The structure is able to transfer the pre-stressing loads from beams to shell elements and therefore allowing a stiffer load bearing structure. Thereby UHPFRC improves tension resistance, post cracking behaviour, dry-fit jointing and efficient material utilization by pre-stressing. This will allow a combination of beam and shell elements to become a modular curved spatial structure (Figure 13).

Depending on the geometric constraints the resulting hybrid structural systems and elements in three dimensional space can work as beams and surfaces as mainly bending loaded components or function as membrane structures

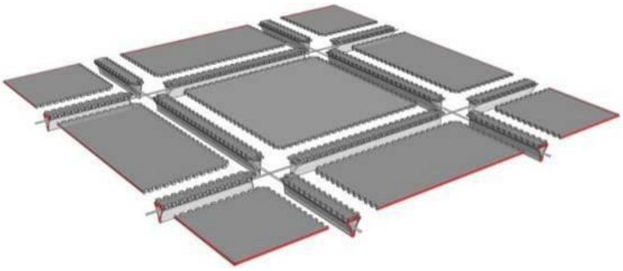

Figure 3: Coffered ceiling with a hybrid grid of shell and spatial elements.

2. Experimental analysis of shell joints

The high precision shell jointing systems shows high load bearing potential in compression and bending tests (Lehmberg *et al.* [1] and Mainka *et al.* [3]). In the previous tests the joint design B2 of dovetail anchors which are shown in the matrix of parameters for shell joints (Figure 4) showed a good overall result for bending and compression. To be able to design a modular hybrid T-beam (Figure 12 right) the bending strength of the plate joint had to be increased and the joint shear strength had to be evaluated with a shell thickness of 15 mm.

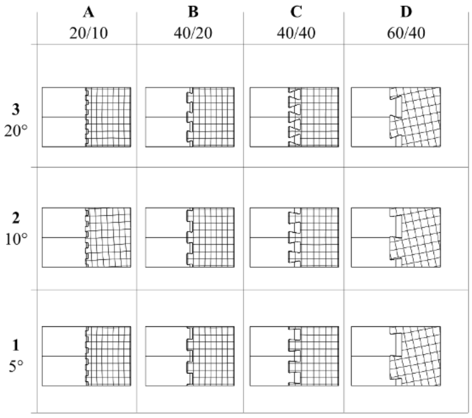

Figure 4: Matrix of parameters for shell dovetail anchor joints, divided in width / height ratio and anchor angle

2.1. Compression tests with UHPFRC joints

In compression tests (Figure 5 left) shell joints with a width of 200 mm were tested. It is shown in Figure 5 (right) that the compressive strength of UHPFRC is transferred through each joint type well. Therefore each joint type is able to transfer the high compression loads in the structure and can thus be used for shell joint design where only compression is present.

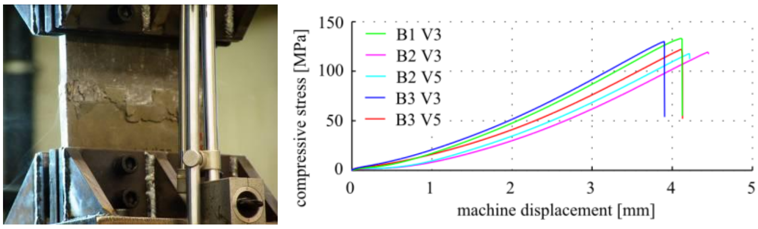

Figure 5: Compressive testing setup (left), results of compression tests (right)

2.2. Bending tests with UHPFRC joints

For bending members as in hybrid spatial and shell members the non standard jointing system has to be able to transfer the UHPFRCs flexural strength. The non standard joints (Figure 4) are not able to transfer the high flexural strength of the UHPFRC because of the smaller effective cross section in bending. To be able to transfer the bending strength the non standard joint was thickened. In addition to tests made with joints in Lehmberg *et al.* [1] the bending strength of locally enhanced bending joints was evaluated. The full flexural strength of the material was reached with doubling the cross section at the joint, 30 mm instead of 15 mm (Figure 6). The local strengthening helped to eliminate this weakened part of the jointing system. Because of the higher jointing force for this new type of joint an UHPFRC inlay was developed which can be added locally to the extended cross section (Figure 6 right).

Figure 6: Advanced bending joint design B2.2 with thickened dovetail anchor (left), B2.3 doubled joint and B2.4 shape optimized joint with UHPFRC inlay (right)

In a 4 point bending test (Figure 7 left) the optimized joints were able to transfer the flexural strength of the UHPFRC (Figure 7 right) and can therefore be used for the design in the modular T-beam structure (Figure 12).

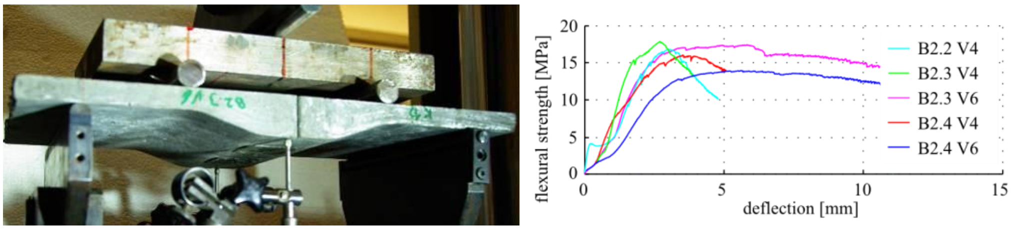

Figure 7: 4 point bending test setup (left), results of bending test for enhanced non standard bending joints (right)

2.3. Shear tests with UHPFRC joints

In a T-beam cross section the shear coupling of the slab and the beam is important to make use of the more rigid and efficient structure, therefore the anchor teeth had to be tested for their shear resistance. Because of the good results of teeth design B2 the design was used to test different shear angles of the joint to analyze the strength for shear (Figure 8). Optical deformation measurement shows the main principal strains, seen as red and yellow colours, which indicate cracks at the peak load of the test. By testing just a two teeth joint design extensive cracking in the shell elements from 0° to 45° can be seen due to notch effects of the anchor. Because of this effect compressive and shear strength was not fully reached in those tests. This premature failure in the plate was not seen at 60°, where the shear failure can be seen within the teeth (Figure 8 right).

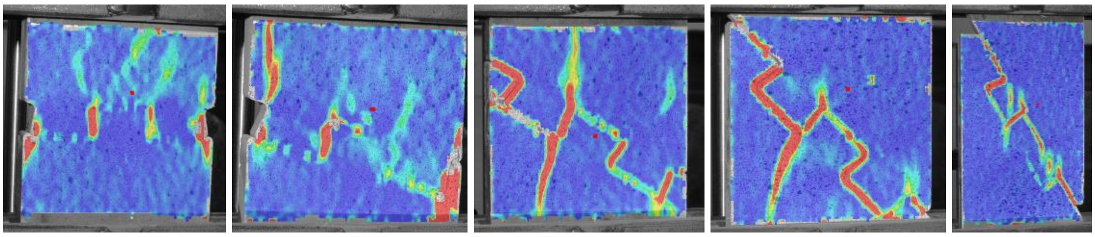

Figure 8: Test setup for vertical compression tests with different joint angles of shear specimens 0°, 15°, 30°, 45° and 60° (from left to right)

To analyze the shear behaviour of the teeth a 90° load direction a test was designed with a UHPFRC base. A model of the test can be seen in Figure 9 (left). The tested shell element was only jointed in the UHPFRC base by two teeth and not connected to the back or the side of the base. The test was done with the teeth design B2 and with the new UHPFRC inlay from the bending test (Figure 6 right). The optical measured strains showed the shear cracking of the teeth as well as a failure in the UHPFRC load block after the test (Figure 9 middle, right).

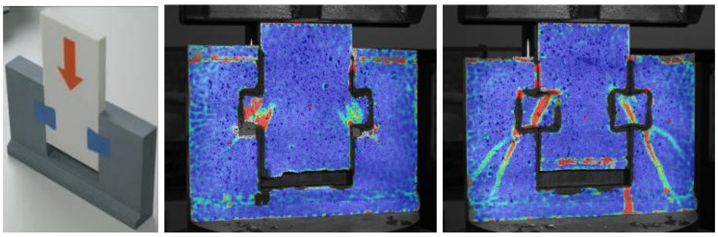

Figure 9: Model of UHPFRC base for 90° shear tests (left), tensile strain with plate (middle) and inlay joint (right) at 90° load direction

The shear results plotted in Mohr’s circle (Figure 10) showed the overall shear resistance which was used to design the shear keys in the large scale tests. Because of the premature failure from 0° to 45° due to load peaks in the area of the teeth (Figure 8) the UHPFRC compressive load was not reached and the shear strength is underestimated. For the 60° and 90° specimens the shear failure can be seen in the optical measured strains (Figure 8 right, Figure 9 middle, right) which indicate the full shear performance of the UHPFRC. The chosen design of the shear teeth can be made with the maximum shear stress due to the fact, that shear will be induced at 90° angle at the coupling of slab and beam in the T-beam structure (Figure 12 right).

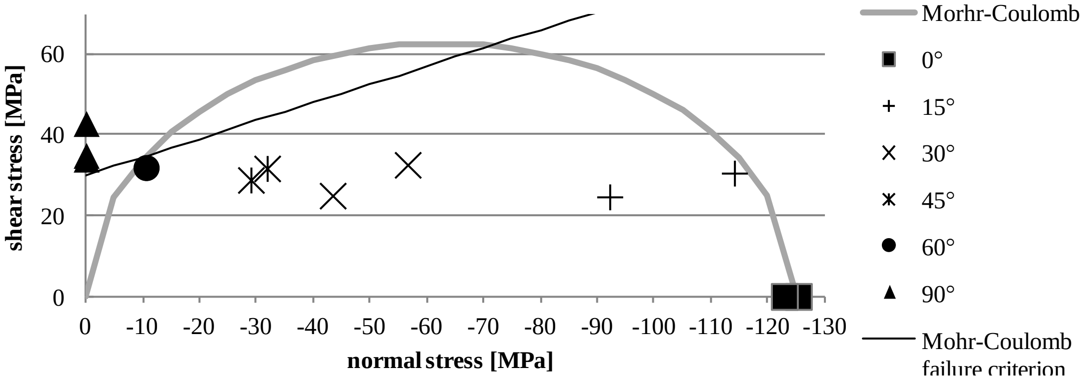

Figure 10: Mohr’s circle with plotted results of non standard joints shear tests

3. Realization of a modular UHPFRC T-Beam

By using the complexity of joints and structures the material strength can be utilized where it is needed. The structural members are built with UHPFRC without regular reinforcement. This allows for a thin wall thickness of 15 mm and a lightweight construction. To achieve the needed tolerances for full scale non-standard joint members the casting process has to be adjusted. This refined the process of the Digital Workflow from designing, computer aided engineering to fabrication with CNC-milled high precision formwork. The modular structure consists of beam and plate elements which are connected by non-standard joints without additional levelling which can be joint on site. For better durability the structural member is pre-stressed by non metallic pre-stressing strands. Because of the high bending strength of the UHPFRC the non-standard joints are able to transfer the required load to create a monolithic structural member. With full scale testing of modular hybrid T-beam members the design process will be verified.

The building of the modular system started and pre-testing began with scaffolding building and testing of new UHPFRC mixtures for the big scale test. Effects of shrinkage and creep are investigated to ensure the high precision of the members. The first tested design is based on linear, non shape optimized members to check for the workability of the non standard jointing system. In the next design phase a shape optimized cross section will be used.

2.1. Formwork and casting of UHPFRC elements

The casting process with a linear non standard jointing member showed the workability of the new admixture and demoulding of the formwork. The plate members were then joined and tested with digital measurements for their building accuracy (Figure 11 e). It showed good accuracy for large 1.3 m shell joints and CNC milled formwork.

Figure 11: CNC fabrication of formwork (a), casting of the specimens (b), protection against demoisturing of casted shell joint (c), demoulding (d), jointed linear shell element (e)

2.1. Modular hybrid shell and spatial T-beam

In the first big scale test for investigating the non standard jointing of hybrid shell and spatial structures a first T-beam will be build. The T-beam will then be tested in a 4 point bending test (Figure 12 right). The developed jointing principles for compression, bending and shear will be used for the joints in beam and shell elements for the T-beam (Figure 12 left). The pre-stressing is done with carbon fibre reinforced plastics (cfrp) strands which are anchored at the ends of the beam (Figure 12 right). The goal is to be able to build the structure with 15 mm wall thickness and just locally enhanced joints for load peaks. Therefore all the developed jointing principles will be used.

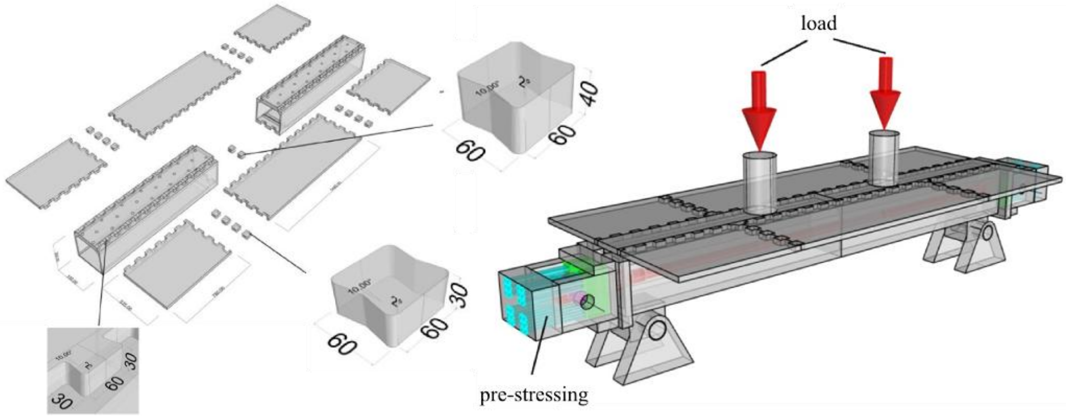

Figure 12: Shell, spatial and joint elements of the tested T-beam (left), jointed T-beam and testing setup (right)

4. Conclusion

By achieving a high mechanical efficiency through increased precision and geometric optimisation of the designed UHPFRC non-standard jointing system a modular lightweight and efficient structural system can be build. The strength of the already developed new jointing principles for UHPFRC components show its potential already, but the goal is to increase the load bearing capacity of structural components and systems by intelligent coupling of individual modular beam and shell elements into hybrid, cooperating supporting elements and systems. By combining dry fit beam members associated with shear resistant flat surface elements, a variety of relevant building structures can be realized. This will allow the combination of beam and shell elements to a modular curved spatial structure (Figure 13). Depending on the geometric constraints the resulting hybrid structural systems and elements in three dimensional space can work as beams and surfaces as mainly bending loaded components or function as membrane structures.

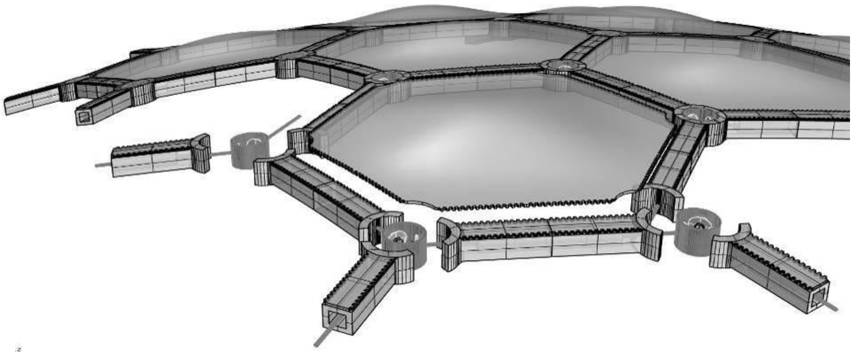

Figure 13: Non standard joints in combination of beam and shell elements to a modular hybrid curved spatial structure

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