Prestressed Sandwich Beams with UHPC Layers

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Abstract:

Sandwich panels with concrete facings and non-metallic reinforcement can fulfill the requirements of sustainable and durable building envelopes. The application of UHPC (ultra-high performance concrete) with high strengths results in a reduction in concrete usage and the realization of thin concrete layers. An additional prestressing with non-corrosive, high-strength CFRP (carbon fiber reinforced polymers) reinforcement enables long spans. In combination with a core of polymeric rigid foam, an enhanced load-bearing capacity of sandwich panels can be reached providing a low weight. In general, sandwich panels with concrete facings are assembled by cutting slabstock foams, which results in fine dust covering the cutting edges and thus harming the bond quality to the concrete facings. In addition air inclusions may occur during concreting the sandwich panels. In order to overcome these issues, i.e. to achieve a homogenous bond quality, the core made of polyurethane (PU) is foamed in pack between hardened concrete layers.

This paper reports on the flexural load-bearing behavior of prestressed sandwich beams with CFRP reinforcement and foamed core.

Keywords:

UHPC, CFRP, prestressed concrete, sandwich construction, experimental testing

1. Introduction and Background

Sandwich constructions are widely used as façade or roof elements, e.g. in buildings or industrial production halls. In general, these sandwich elements have two outer layers made either of steel or reinforced concrete. The latter usually possesses large thicknesses, but high load-carrying capacities. In between the concrete layers a slabstock foam core is used. The steel layers and steel reinforcement in conventional concrete layers are vulnerable to corrosion in humid environments. Hence, for load-bearing structures thick concrete coverings are necessary (EC2 (2011); FIB (1990); ACI (2005)), which leads to massive elements with high weight. Nevertheless, even thick layers cannot guarantee the corrosion resistance over decades. This issue can be addressed by replacing the conventional steel reinforcement with non-corrosive reinforcement materials, made of carbon fibers with a high tensile strength (up to 3000 MPa). This alternative allows slender structures with high potential for economic savings in terms of materials and transport, as well as reduced time and effort during mounting. Generally, applications for reinforcement meshes or bars, as well as pre-tensioned strands are feasible. Pre-tensioned CFRP reinforcement has been investigated in terms of bond behavior to concrete and structural performance (e.g. Lu et al (2000); Soudki, Green and Clapp (1997); Stark and Hegger (2011)). Applications of CFRP as pre-tensioned reinforcement already show the potential of the high strength material. Additionally, an application of high strength concrete, e.g. ultra-high performance fiber reinforced concrete

(UHPC) is advantageous for further reduction in thickness due to the high tensile strengths (e.g. Zani et al. 2014).

The load-bearing behavior of sandwich members is determined by stiffness and strength of concrete facings and core material, connecting devices, as well as the bond strength between concrete and core, which depends on the production method (Shams and Hegger (2014); Shams et al. (2015)). Typical production methods of sandwich panels with concrete facings using slabstock foams are problematic for consistently ensuring a high bond quality between core material and concrete layers. For this reason, a different process was applied in which polyurethane is foamed between hardened concrete layers (Shams and Hegger (2014); Shams et al. (2015)).

Combining these innovative concrete elements to load-bearing sandwich constructions leads to modern building envelopes. These require high strength to weight-ratios and simultaneously fulfill structural and physical demands such as heat and sound insulation by using polyurethane as the core material between the concrete facings.

2. Testing Methods

Structural façade and roof elements are subjected to snow, wind and temperature loads. Concrete members are additionally subjected by creep and shrinkage. For the prediction of the load –bearing behavior of prestressed sandwich elements with foamed core and UHPC facings, experimental and theoretical investigations are necessary.

Besides bond tests and tests on the transfer length of CFRP prestressing reinforcement in UHPC, small-scale tensile and shear tests on sandwich panels have been conducted. With these information, beam tests on the flexural behavior have been carried out, which are presented in this paper. For detailed results of bond tests on CFRP and small-scale tests on sandwich panels it is referred to (Stark and Hegger (2011); Stark and Hegger (2014); Shams et al. (2015))

2.1. Material Characterization

2.1.1. Ultra-High Performance Concrete

All specimens were fabricated using the same concrete mixture for UHPC with high strength steel fibers (Stark and Hegger (2011)) which was developed within the priority program 1182 of the German Research Foundation (Table 1).

Table 1. UHPC Mixture

Material	Quantity [kg/m³] ([lb/gal])
Cement Cem I 52,5 R HS-NA	825.0 (8.3)
Silica Fume	175.0 (1.8)
Quartz Powder W12	200.0 (2.0)
Sand 0,125 – 0,5 mm	975.0 (9.8)
Steel Fibers (0.9 Vol.-%)	70.7 (0.7)
Water	175.0 (1.8)
Superplasticizer	27.5 (0.3)

The steel fibers had a length of 9 mm (0.35 in) and a diameter of 0.17 mm ($6.7\cdot10^{-3}$ in). The steel fiber ratio in the mixture was chosen to 0.9 Vol.-% leading to an enhanced ductile behavior and good pouring quality. Higher ratios do not necessarily lead to significantly better ductility and bond behavior of strands (Hegger and Bertram (2010)), but to ineffective pouring, since local conglomerations of fibers often take place without proper bond to the concrete matrix. Steel fibers were used rather than non-metallic fibers, since a wide range of experience exists and only corrosion of the fibers at the concrete surface occurs, which does not affect the durability of the structure.

For the fine grained UHPC with a maximum grain size of 0.5 mm (0.02 in) an uniaxial compression strength (cube 150x150x150 mm^3 (5.9x5.9x5.9 in^3) of about 170 MPa (24.6 ksi) and a Young's Modulus of about 44,000 MPa (6,400 ksi) were observed after 28 days. After one day the uniaxial compression strength was about 65 MPa (9.4 ksi) and the Young's modulus about 32,000 MPa (4,640 ksi). The bending tensile strength (40x40x160 mm^3 (1.6x1.6x6.3 in^3)) was approximately 7.5 MPa (1.1 ksi) after one day and 19 MPa (2.8 ksi) after 28 days. All tests were conducted in accordance with DIN EN 196-1, DIN EN 206-1 and EC2 (2011). The results show a low coefficient of variation (COV) of less than 6% for testing after 28 days.

2.1.2. Reinforcement

Pre-tensioned CFRP tendons are applicable for slender concrete structures because of their high tensile strength and high corrosion resistance, which is necessary due to the lack of sufficient concrete covering. The Poisson's ratio of CFRP usually varies between 0.02 and 0.27 (FIB (2007)). The thermal expansion in transverse direction is about 10 to 40 times higher than in longitudinal direction (FIB (2007); ACI (2011)). Experiments at 100°C (212°F) showed a reduction in ultimate limit strength of 20 to 40 % (FIB (2007)). These facts have to be kept in mind for the application of CFRP in buildings or bridges.

For the experimental studies a strut and a seven-wire strand were used as pre-tensioning members provided by TOKYO ROPE MFG. CO., Ltd.. The trade name is CFCC® (carbon fibre composite cable). The material properties, given by the manufacturer are listed in Table 2.

Table 2. CFRP Material Properties

Designation [-]		Diameter [mm] ([in])	Eff. cross-sectional area [mm^2] ([in^2])	Guaranteed capacity [kN] ([kip])	Young's Modulus [GPa] ([ksi])
	U 5.0∅	5.0 (0.2)	15.2 (0.024)	38 (8.5)	167 ($24.2 \cdot 10^3$)
	1x7 7.5∅	7.5 (0.3)	31.1 (0.048)	76 (17.1)	155 ($22.5 \cdot 10^3$)

Bond tests on pre-tensioned CFRP (1350 MPa = 9,300 ksi) in UHPC showed bond stresses up to 25 MPa (3.6 ksi) and transfer length of less than 140 mm (5.5 in) after one day of concrete hardening (Stark and Hegger (2011)).

2.1.3. Core Material

The PU core used in the experimental studies is a mixture of two components, which exhibits a density of about 90 kg/m^3 (0.9 lb/gal). All sandwich sections were foamed in pack. In Figure 1 the general production method is illustrated schematically. In the first step of production, the pre-cast concrete elements were produced (either reinforced or prestressed with CFRP). After curing, the hardened concrete elements were fixed in a wooden formwork (Figure 1, left) and polyurethane components were mixed and poured between the two concrete layers. Afterwards, the formwork was closed and due to the expansion of the polyurethane and resulting pressure, the density as well as homogenous and repeatable bond quality could be controlled.

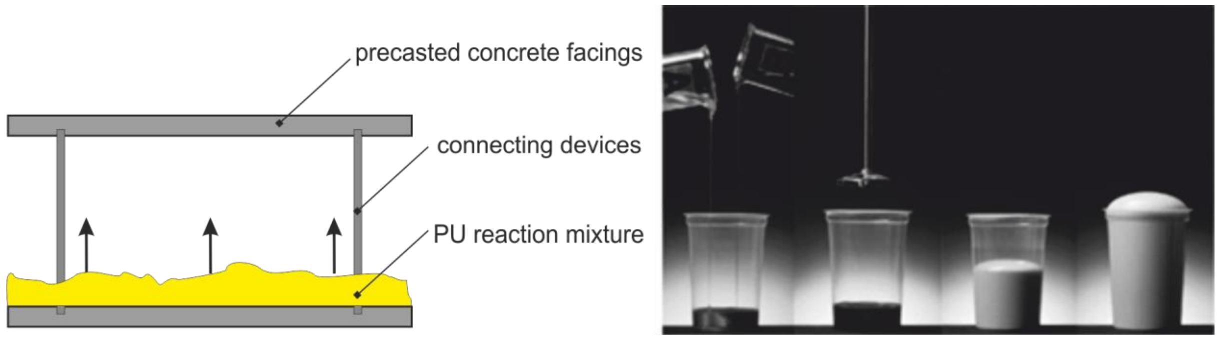

Figure 1. Schematic Diagram of Foaming in Pack (photo: BASF; Shams (2015))

The mechanical properties of the PU foam were determined by tensile, compressive, and shear tests, in accordance with (DIN 826; DIN 1607; DIN 12090). The compressive strength was approximately 950 kPa (138 psi) with a Young's modulus of 32,000 kPa (4,640 psi). The tensile strength was measured to 580 kPa (84 psi) with a Young's modulus of 45,000 kPa (6,530 psi). Under shear load, the strength was determined to 570 kPa (83 psi) with a shear modulus of 11,500 kPa (1,670 psi). All material properties had relatively low standard deviations of less than 15 %.

Small-scale tests on sandwich elements showed high, repeatable bond stresses under tensile and shear loading between core foam and UHPC layers. Maximum tensile stresses of 300 kPa (36 psi) and shear stresses of 270 MPa (39 psi) could be reached without any further treatment of the UHPC surface. In either loading cases a shear grid (see 2.1.4) led to a ductile post peak behaviour.

2.1.4. Connecting Devices

The application of non-metallic connecting devices causes less thermal bridges in the cross-section than commonly used metal connectors. Furthermore, the connectors have generally three functions. They act as spacers between the inner and outer concrete layers before the panels are foamed with PU mixture and they carry acting tensile forces during the foaming process. Besides, they bear shear loads induced by shrinkage of the layers, thermal expansions and bending of the elements. In the current investigations, only a continuous connecting device was used, since the foaming process of the relatively small specimens could be handled easily.

In the conducted flexural tests an epoxy coated mesh-like textile was cut under 45° (Figure 2) to sustain shear loads. The Young's modulus was about 235 GPa (34,000 ksi) with a tensile strength of about 1,650 MPa (240 ksi). These material properties were given by the manufacturer.

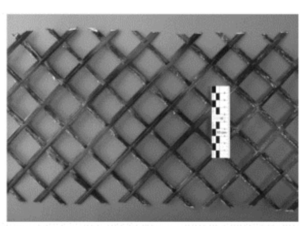

Figure 2. CFRP Shear Grid (cut under 45°)

In case of an application, the shear grid was embedded 30 mm (1.2 in) into each of the two UHPC layers to ensure sufficient bond strength.

2.3. Flexural Testing of Prestressed Sandwich Elements

For the investigation of the flexural load carrying behavior three-point bending tests were performed. Figure 3 shows the test setup of the 2.4 m (7.9 ft) long beam elements. Either UHPC layers were 60 mm (2.4 in) thick.

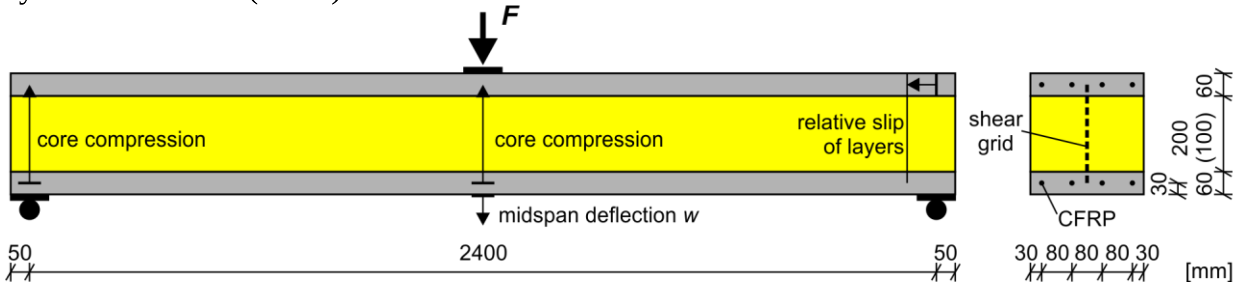

Figure 3. Setup of Flexural Testing Including Measuring Technique (25.4 mm = 1 in)

Types of CFRP reinforcement (none (---), single wire (W) and seven-wire strand (S)), prestressing of top and bottom layers as well as core height were varied (Table 3).

Table 3. Test Specimens of Flexural Testing

Test [-]	Reinforcement Bottom	Reinforcement Top	Prestressing bottom [MPa] ([ksi])	Prestressing top [MPa] ([ksi])	Core height [mm] (in)	CFRP shear grid [-]
1	---	---	---	---	200 (7.9)	---
2	4 W	4 W	---	---	200 (7.9)	---
3	4 W	4 W	---	---	200 (7.9)	One
4	4 S	---	675 (98)	---	200 (7.9)	One
5	4 S	4 W	675 (98)	---	200 (7.9)	---
6	4 S	4 S	675 (98)	675 (98)	200 (7.9)	One
7	4 S	4 W	675 (98)	---	100 (3.9)	One

The pre-tensioning was chosen considerably low, since elements with only 2.4 m (7.9 ft) span were tested.

The load, deflections, core compressions, relative displacements of the UHPC layers and concrete strains were measured during testing. At test day, the material properties of the UHPC were determined. The elements were loaded continuously over their width with a constant displacement rate of 1 mm/min (0.04 in/min).

3. Results

This section presents the results of seven flexural beam tests. In Table 4 the detailed material properties of UHPC, maximum load F_{max}, corresponding mid span deflection w_{max} and main failure type are reported.

Table 4. Test Results of Flexural Testing

Test [-]	Layer [-]	$f_{cm,cube,28d}$ [MPa] ([ksi])	$E_{cm,28d}$ [MPa] ([ksi])	$f_{ctm,flex,28d}$ [MPa] ([ksi])	F_{max} [kN] ([kip])	w_{max} [mm] ([in])	Failure [-]
1	Bottom	170 (24.7)	41,300 (6,000)	19.3 (2.8)	47.8 (10.8)	23.2 (0.91) ≅ L/100	Bottom layer PU Core
	Top	170 (24.7)	41,300 (6,000)	19.3 (2.8)			
2	Bottom	175 (25.3)	44,700 (6,500)	17.7 (2.6)	57.8 (13.0)	30.6 (1.20) ≅ L/80	PU Core
	Top	175 (25.3)	44,700 (6,500)	17.7 (2.6)			
3	Bottom	167 (24.2)	47,000 (6,800)	21.1 (3.1)	90.9 (20.4)	38.8 (1.53) ≅ L/60	PU Core
	Top	165 (23.9)	46,100 (6,700)	19.5 (2.8)			
4	Bottom	167 (24.2)	47,000 (6,800)	21.1 (3.1)	85.0 (19.1)	28.7 (1.13) ≅ L/80	PU Core
	Top	165 (23.9)	46,100 (6,700)	19.5 (2.8)			
5	Bottom	172 (24.9)	44,000 (6,400)	18.7 (2.7)	52.1 (11.7)	20.7 (0.81) ≅ L/120	Bond zone
	Top	169 (24.5)	42,400 (6,200)	19.0 2.8)			
6	Bottom	171 (24.7)	43,500 6,300)	17.6 (2.5)	87.1 (19.6)	29.2 (1.15) ≅ L/80	PU Core
	Top	169 (24.5)	43,200 (6,300)	19.9 (2.9)			
7	Bottom	169 (24.5)	42,400 (6,200)	19.0 (2.8)	53.2 (12.0)	30.1 (1.19) ≅ L/80	Bond Zone
	Top	172 (24.9)	44,000 (6,400)	18.7 (2.7)			

Test 1 serves as reference test without prestressing nor application of shear grid. This test mainly failed due to rupture of the bottom layer.

The failure loads generally increase for discretely reinforced or prestressed bottom and top layers. Maximum midspan deflections decrease in prestressed elements. However, large deflections of up to L/60 (minimum L/120) were reached, which included a failure indication due to multiple cracking in the bottom layer. Due to the high tensile strength of the applied UHPC with steel fibers, the crack widths remained much smaller than half fiber length, i.e. fibers were still carrying load. In four of seven tests, a failure of core material could be reached, which indicates a high bond strength of the interface between UHPC and PU foam. In three cases, failure of PU core was not determining, since either no CFRP reinforcement was applied or the core height was halved.

Subsequently, three tests are inspected closely. In Figure 4 (left) the load-deflection behavior of test specimen 3, 6 and 7 are exemplarily shown until maximum load. In all cases the load decreased rapidly to less than 30 % after reaching the maximum load. Compared to tests 3 and 6, test 7 reached the lowest load since the core height was only 100 mm (3.9 in). Test 3 and 6 sustained roughly the same load. The deflection of test 6 could be reduced by prestressing of top and bottom layers. In Figure 4 (right)) the crack patterns are shown. The prestressing of bottom and top layer in test 6 led to least cracks in either UHPC plates. No prestressing in test 3 resulted in relatively even spaced cracks over the full length with small crack widths. With a core height of 200 mm (7.9 in) the core material failed. In contrast, the specimen with 100 mm (3.9 in) core height failed in the bond zone.

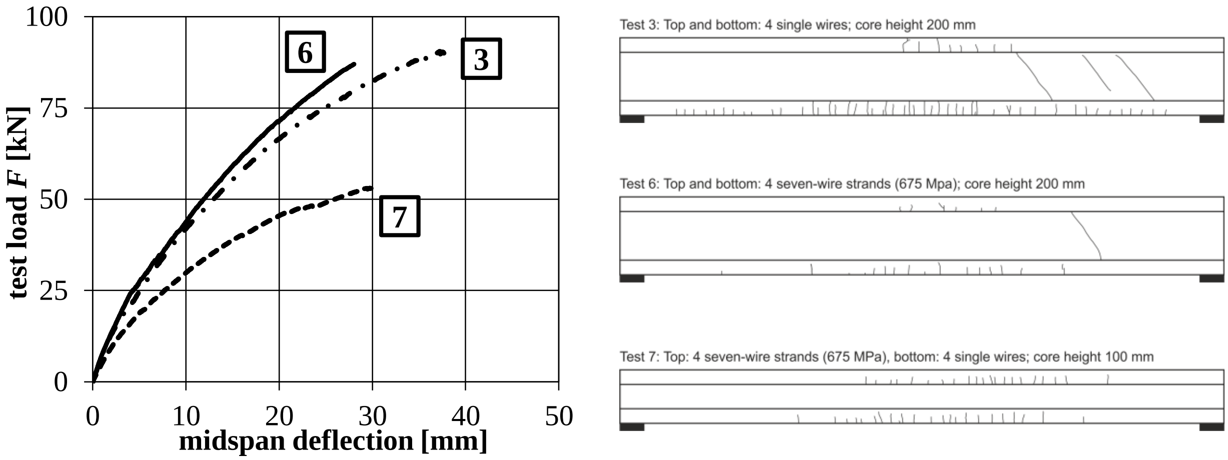

Figure 4. Representative Load-Deflection Curves (left) and Crack Patterns of tests 3, 6 and 7 (right); (25.4 mm = 1.0 in and 10 kN = 2.5 kip)

In Figure 5 (left) the results of the core compressions at midspan and support are depicted for test 6 and 7. At the beginning of the tests the core material compresses linearly. After reaching 35 kN (7 kip) in test 6 an smooth increase in core compression above average can be noticed. In contrast, test 7 with half the core height shows a large increase above 20 kN (4.5 kip). The compressions at support are roughly 20-30 % greater compared to midspan.

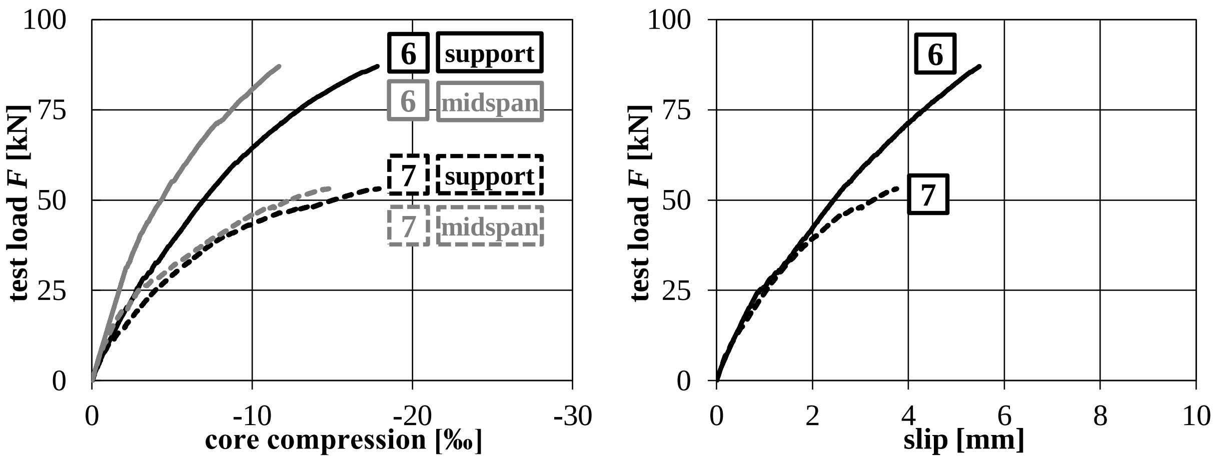

Figure 5. Representative Load-Core Compression (left) and Load-Slip (right) Relationships for Test 6 and 7; (25.4 mm = 1.0 in and 10 kN = 2.5 kip)

Figure 5 (right) shows the influence of the core height on the relative slip of the UHPC layers for tests 6 and 7. The progression is very similar until a loading of 20 kN (4.5 kip), but slip increased over average for test 7 until failure.

4. Discussion

The test results already show a high potential of prestressed, foamed in pack sandwich elements with UHPC layers, even though only beams elements with 2.4 m (7.9 ft) span and 0.3 m (11.8 in) width were tested. Further testing of large elements will show if the influence of prestressing and bond behavior between core foam and UHPC layers will be more significant as for the tested specimens.

The material properties of UHPC show high strengths and Young's moduli. The coefficient of variation (COV) was determined to less than 6 %, which shows a good reproducibility.

From the load deflection curves it can be seen that prestressing of the layers has a high influence on the load-deflection and cracking behavior. Nevertheless, prestressing did not necessarily led to higher maximum loads, but to less deflection (see tests 3 (no prestressing) and 6 (prestressing of both layers)). Since CFRP does not show a significant yield point, less remaining load capacity is available after decompression (load which induces first tensile stresses in prestressed member). Nevertheless, prestressing can be important for serviceability, if sufficient indication of failure is given, e.g. due to cracking of the layers. The application of a shear grid reduces the relative displacement of the UHPC layers and leads to a large increase in maximum load (test 4 and 5), since the probability of a bond failure is reduced. The core height was decreased from 200 mm (7.9 in) to 100 mm (3.9 in) in test 7. Compared to test 4 (200 mm (7.9 in)) the same maximum deflections were observed, but only 60 % of the maximum load were reached. The reference test 1 with no CFRP reinforcement in either layer and no shear grid showed a poor load-carrying behavior with low maximum load and deflection, as expected.

The compression strains of the core material progress in the same manner for all tests for the same load steps. As expected, the core compression at the supports is higher than at midspan. Core compression in test 7 were in the same range as for other test with 80 % higher maximum loads. This fact needs further investigation.

The influence of the prestressing can be analysed by the crack patterns. Prestressed bottom and top layers, were less ductile with less cracks during testing. Future tests on long span beam elements have to show the influence of prestressing in detail.

5. Conclusions

The first flexural tests on load-bearing sandwich panels with UHPC layers, foamed PU and pre-tensioned CFRP brought up the following key results:

- Foaming in pack of PU between hardened UHPC layers enables high bond strength;
- Bottom layers need discrete reinforcement, either pre-tensioned or untensioned;
- CFRP shear grids enhance the load-carrying behavior in terms of maximum load and reduced deflections. Relative slip between UHPC layers was decreased and prevented debonding between concrete and PU;
- Prestressing of CFRP did not lead to higher maximum load, but to less deflection for spans of 2.4 m (7.9 ft);
- Decreasing the core height led to a massive reduction in maximum load.

Further experimental investigations are required to investigate the influence of different variations of pre-tensioning forces in the UHPC layers, PU core thicknesses, thicknesses of the UHPC layers and lengths of the sandwich elements. It has to be investigated in tests on long span beam elements, if the production technique by foaming in pack of PU performs as good as in current tests. If so, considering bond action for design seems possible and will lead to a reduction in material usage or higher possible loads compared to nowadays sandwich panels.

One additional key factor for an application to buildings is the investigation of the fire resistance and performance, respectively. Besides, long-term tests will be necessary to investigate the time-dependent material behavior of UHPC, CFRP and especially creep of the PU core foam.

6. References

ACI 318-05/318R-05, "Building Code Requirements for Structural Concrete and Commentary", *ACI Committee 318*, American Concrete Institute, 2005.

ACI 440.4R-04, "Prestressing concrete Structures with FRP Tendons", *ACI Committee 440*, 2004 (Reapproved 2011).

CEB-FIB Model Code 1990, Thomas Telford Ltd, London. 1993.

DIN EN 196-1, "Method of Testing Cement – Part 1: Determination of Strength", German Version EN 196-1:2005.

DIN EN 206-1, "Concrete – Part 1: Specification, Performance, Production and Conformity", German Version EN 206-1:2000.

DIN EN 826, "Thermal Insulating Products for Building Applications – Determination of Compression Behavior", German Version EN 826:2013.

DIN EN 1607, "Thermal Insulating Products for Building Applications – Determination of Tensile Strength Perpendicular to Faces", German Version EN 1607:2013.

DIN EN 12090, "Thermal Insulating Products for Building Applications – Determination of Shear Behavior", German Version EN 12090:2013.

EC2, "Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings", German version EN 1992-1-1:2004 + AC:2010, *European committee for standardization (Cen)*, January 2011.

FRP Reinforcement for RC Structures. Technical Report on the Design and Use of Fibre Reinforced Polymer Reinforcement (FRP) for Reinforced Concrete Structures, *fib Bulletin 40*, 2007.

Hegger, J.; Bertram, G., "Verbundverhalten von vorgespannten Litzen in UHPC, Teil 1: Versuche zur Verbundfestigkeit und zur Übertragungslänge" (Bond Behavior of prestressed Strands in UHPC. Part 1: Tests on Bond Strength and Transfer Length), *Beton- und Stahlbetonbau (Concrete and Reinforced Concrete Structures)* Volume 105, Issue 6, 2010, pp. 379-389.

Lu, Z.; Boothby, T.; Bakis, C.; Nanni, A., "Transfer and Development Lengths of FRP Prestressing Tendons", *PCI Journal*, March-April 2000, pp. 80-91.

Shams, A.; Hegger J., "Experimental Investigations on TRC sandwich panels with foamed PU cores", *Proceedings of the 10th fib international PhD Symposium in Civil Engineering*, July 21-23, 2014, Université Laval, Québec, Canada, pp.327-332.

Shams, A.; Stark, A.; Hoogen, F.; Hegger, J.; Schneider, H., "Innovative sandwich structures made of high performance concrete and foamed polyurethane", *Composite Structures*, Vol. 121, March 2015, pp. 271-279.

Soudki, K.; Green, M.; Clapp, F., "Transfer Length of Carbon Fiber Rods in Precast Pretensioned Concrete Beams", *PCI Journal*, September-October 1997, pp. 78-87.

Stark, A.; Hegger, J., "Verbundverhalten von CFK-Spannbewehrungen in UHPFRC" (Bond behavior of pre-tensioned CFRP tendons in UHPFRC), *Beton- und Stahlbetonbau (Concrete and Reinforced Concrete Structures)*, Volume 108, No 10, 2013, pp. 701-710.

Stark, A; Hegger, J., "Development of CFRP Pre-tensioned Sandwich Panels with Concrete Facings", *CICE 2014: The 7th International Conference on FRP in Civil Engineering*, Vancouver, Canada, August 20-22, 2014. ISBN 978-1-77136-308-2, p. 210 (full paper on CD-ROM).

Zani, G.; Colombo, M.; di Prisco, M., "High Performance Cementisious Composites for Sustainable Roofing Panels", *10th fib International PhD Symposium in Civil Engineering*, Québec, Canada, July 21-23, 2014.

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