PRECAST STRUCTURAL ELEMENTS MADE OF UHPC

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Abstract

Prestressed segmental hollow core slabs made of UHPFRC represent an effective structural system. The experimental research has been conducted in order to investigate their structural performances and the possibility of their production. A prototype 2 m long and 1.5 m wide was tested. Additional tests on material were also carried out. The segments of the hollow core slab were cast in vertical position which resulted in an excellent quality of the surface and easy production, because the formwork of longitudinal openings may be easily pulled out in a short time after casting. The distribution of fibres is influenced by the casting method of the elements. Most of fibres tend to be in horizontal position during casting process. Additional bending tests on strips cut from slabs cast in horizontal and vertical positions also showed that the performance of individual strips may be significantly variable. It can be concluded that the casting method is important and it should be taken into account when designing the technology of production.

Résumé

Les dalles alvéolées précontraintes en BFUP représentent un système structurel efficace. Une recherche expérimentale a été menée afin d'étudier leurs performances structurelles et la possibilité de leur production. Un prototype de 2 m de long et 1,5 m de large a été testé. Des tests supplémentaires sur le matériau ont également été exécutés. Les éléments de dalle alvéolée ont été coulés en position verticale, ce qui a donné une excellente qualité de la surface et une production facile, car le coffrage des ouvertures longitudinales peut être facilement retiré dans un court délai après le bétonnage. La distribution des fibres est influencée par le mode de bétonnage des éléments. La plupart des fibres ont tendance à être en position horizontale pendant le bétonnage. Des tests de flexion supplémentaires sur des bandes découpées dans des dalles coulées en position horizontale et verticale ont également montré que la performance de chaque bande peut ętre significativement variable. On peut conclure que le mode de bétonnage est important et qu'il doit être pris en compte lors de la conception de la technologie de production.

1. INTRODUCTION

Development of new materials opens opportunities of designing new structures. UHPC – or more precisely UHPFRC – provides a possibility to design light and durable structures. Although UHPFRC is a high strength material, there is still a big difference between its compression and tensile strengths. This shortcoming may be overcome using prestressing. Usually prestressing is used in longitudinal direction. In the transversal direction, a classical reinforcement may be used or a limited tensile strength of UHPFRC may be able to cover the stresses induced by dead and applied loads if the amount of fibres is sufficient. An experimental research is focused on the development of a hollow core slab, which could be used as a deck for a small segmental bridge. An experimental prototype of the slab was cast and the technology of production and structural performance of the prototype was investigated. Additional material tests have been carried out in order to compare the performance of laboratory samples and of the prototype.

2. MATERIAL USED FOR THE PROTOTYPE

UHPC was developed from local constituents available in the Czech Republic. The cement CEM I 42.5 R was used together with aggregate, silica fume and admixtures. High strength steel fibres (0.3 mm diameter and 17 mm long) were added in the amount of about 2% in volume. The concrete mix is designed for ready mixed concrete, i.e. it can be transported in the truck mixer and delivered to the places approximately up to 30 km from the mixing plant. The parameters of the hardened concrete were obtained from several tests.

The mean compressive strength measured on standard cylinders (150 x 300 mm) was 140 MPa. The mean value of the elastic modulus is 46.3 GPa. The aim of the project was also to test a cheaper alternative of the material, where constituents usually available on the mixing plant were used. Therefore mechanical parameters were lower than at the originally developed material, but the tests of the resistance against de-icing salts showed very good results. The parameters defining the tensile properties of the UHPC were the most interesting. The direct tensile strength was measured on the cylinders of 60 mm diameter and 120 mm long which were taken as drilled cores from the prototype of the hollow core slab (Table 1). It is necessary to note that the tensile strength of cores is influenced by the drilling process.

Then the flexural strength was measured using 4 point bending tests on prismatic samples (150 x 150 x 700 mm) without notch. The span of the supports was 600 mm and the distance between loads was 200 mm. One part of the research also involved the effect of the casting method on the structural response of the element. Therefore the two sets of laboratory beams were cast. The first set of 6 beams was cast classically in the horizontal position. The other 6 beams were cast in vertical positions like columns.

Table 1: Direct tensile strength (cores ∅60 mm, length 120 mm)

Core No.	1	2	3	4	5	6	Mean strength	St. dev.
Tensile strength [MPa]	5.2	3.9	4.9	5.7	4.6	4.5	**4.8**	**0.59**

Table 2: Measured flexural strength (beams cast in a horizontal position)

Beam no. Dir. of cast.	Tensile strength [MPa]	Residual tensile strength [MPa]		
		$\delta_1 = 1.0$ mm	$\delta_2 = 2.0$ mm	$\delta_4 = 4.0$ mm
H1 - Horizontal	15.3	15.1	10.7	2.3
H2 - Horizontal	15.7	12.3	7.9	2.9
H3 - Horizontal	16.8	15.7	13.4	7.1
H4 - Horizontal	15.5	14.5	11.2	5.0
H5 - Horizontal	14.9	12.6	8.8	3.6
H6 - Horizontal	16.7	15.9	11.5	4.8
Mean value	**15.8**	**14.4**	**10.6**	**4.3**
Standard dev.	**0.8**	**1.6**	**2.0**	**1.7**

Table 3: Measured flexural strength (beams cast in a vertical position)

Beam no. Dir. of cast.	Tensile strength [MPa]	Residual tensile strength [MPa]		
		$\delta_1 = 1.0$ mm	$\delta_2 = 2.0$ mm	$\delta_4 = 4.0$ mm
V1 - Vertical	13.6	9.6	7.7	3.3
V2 - Vertical	14.9	12.1	7.7	2.7
V3 - Vertical	14.1	11.3	8.2	2.7
V4 - Vertical	13.3	8.4	3.5	1.6
V5 - Vertical	13.9	12.2	9.5	4.7
V6 - Vertical	13.0	10.1	7.4	3.0
Mean value	**13.8**	**10.6**	**7.3**	**3.0**
Standard dev.	**0.7**	**1.5**	**2.0**	**1.0**

After 28 days all the beams were tested. The results are summarised in the Tables 2 and 3. The residual flexural strength at the deflection of 1, 2 and 4 mm is also recorded.

From the Tables 1, 2 and 3, it may be concluded that the direct tensile strength is significantly smaller than the flexural strength, which is generally known. However, the difference between the flexural and tensile strength is higher than that assumed for ordinary concrete e.g. in the Eurocode.

The results in the Table 2 and 3 clearly indicate that the direction of casting of concrete is necessary to take into account since it influences the structural performance. The difference in the average value of the flexural strength is about 2 MPa, but at the residual tensile with the deflection 1 mm the difference is almost 4 MPa, which means that the effect of fibres is much smaller when the beams were cast in vertical position. The distribution and orientation of fibres is dependent on the direction of casting, which needs to be considered, when the casting method of structural elements is designed.

3. EXPERIMENTAL PROTOTYPE

The prototype of the hollow core slab is 2 m long and 1.5 m wide. The thickness of the slab is 300 mm. The longitudinal openings have a triangular shape, which has the advantage to lighten the slab. The idea is to cast segments of the slab 2 m long, which would be connected by unbonded prestressing located in the longitudinal openings. The difficulty may be found in the production of the slab. Casting of the slab in vertical position seems to be a reasonable alternative, since an excellent quality of all surfaces may be obtained and also it is feasible to pull out the formwork of the openings early after casting of concrete. The steel mould, which has steel triangular elements as a formwork of the openings, was produced and filled from the top by self-compacting UHPFRC. The formworks of the openings (cores) are conical, which means that the openings on the top of the mould are slightly larger than the openings at the bottom part. The elements are easy to pull out in about 4 – 6 hours after casting of concrete in dependence on the ambient temperature. It is also important to pull the internal formwork (the conical elements) rather early, because they are very stiff and they prevent shrinkage concrete, autogenous shrinkage in particular, which might result in tensile stress and internal damage of concrete at very early age, when its tensile strength is rather low. The picture of the prototype of the hollow core slab is shown in Fig. 1.

Figure 1: Prototype of the hollow core slab

4. TESTING OF THE PROTOTYPE

The prototype was tested in bending in the longitudinal and transversal direction. Tests in the longitudinal directions are not described here, because of the limited space. In the transversal direction the prototype is not prestressed. The objective of the testing was to investigate the performance of the prototype and to specify the realistic load which may be transferred by the slab reinforced only with fibres. In order to use the prototype more efficiently, it was divided into 4 elements (designated later P1 – P4), as it is possible to see in Fig. 1. Each element was 1.5 m long and 0.475 m wide (the rest was lost during sawing). The arrangement of the 3 point bending test is shown in Fig. 2. The span of the slab is 1.4 m and a single load is located at the midspan. The first model was cast in the steel mould without any special arrangements. After about 6 hours the steel formwork of the openings was pulled out and the element was left the mould for about 3 days. During this time it was covered by PE foil, so that its drying was minimized. Then it was removed from the mould and left outside.

Figure 2: Arrangement of the 3 point bending test

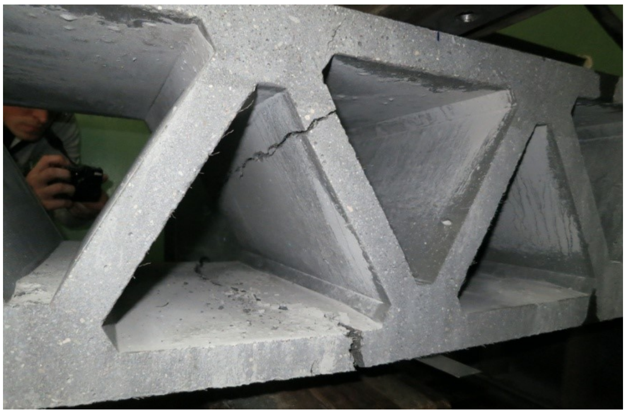

Figure 3: Main crack resulting in failure of the slab

Three elements were tested at the age of 28 days (P1, P3 and P4) and one (P2) was left in the water for a period of 1 year. Then it was also tested. The loading was controlled by deflection of the slab, so that the descending branch of the load – deflection curve was also obtained. The failure of the slab is a result of the failure of the bottom thin layer of UHPC which is subjected to almost direct tension, since the slab may be considered as a wide truss girder (Fig. 3).

The individual elements of the prototype have different thicknesses of the top and bottom slab and of the partitions between the openings, which is a result of conical shape of the formwork. The structural response of individual elements (P1 – P4) of the prototype cannot be directly compared, because of the different dimensions. Instead of the load deflection curves, the response was recalculated and so called reference stress in bottom slab of the truss was taken as a parameter for comparison of individual tests. The reference stress is calculated as an approximate tensile force in the bottom flange divided by the cross-sectional area of the bottom flange. If the element was a real truss, then the value of reference stress would be equal to tensile stress. Since the element is not a truss, there are no hinges in nodes, but the flanges and partitions between openings work as a frame, the tensile stress is not distributed uniformly and the real tensile stress will be different from the reference stress. The variation of reference stress on the deflection is plotted in Fig. 4. (It is necessary to remind again that the element P2 was tested at the age of 1 year and it was most of the time stored in water).

The elements P1 to P4 are cut from one prototype. The element P1 has the smallest thickness of the flanges and partitions, the element P4 the highest thickness. It may be observed that the elements P1 and P3 have smaller ultimate load (ref. stress) than the elements P2 and P4. It may be possible that the thin parts were subjected to damage due to restrained deformation at early stage of hardening, when autogenous shrinkage develops. There is an experience from earlier research that the autogenous shrinkage develops as early as the hardening starts. The element P4 has larger thickness of individual parts of the cross-section and it may happen that it is less sensitive to the strain induced by autogenous shrinkage. Also it may happen that the thicker parts are more heated due to the hydration which may accelerate the strength development. The element P2 was stored in water for 1 year. Its tensile strength increased due to the higher age of concrete at the time of testing and also possible microcracks were healed themselves because of the water treatment. This element, although it is the second thinnest, exhibited the highest load carrying capacity.

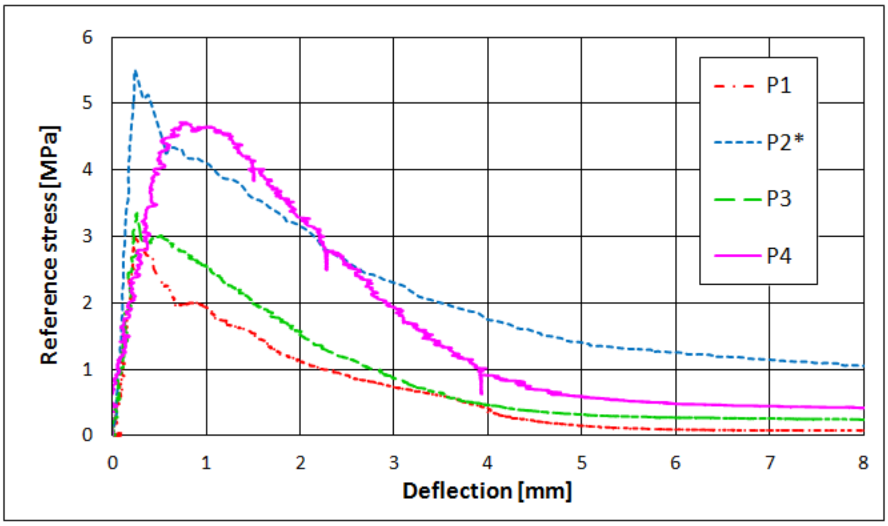

Figure 4: Reference stress in dependence on the deflection (prototype 2015)

The second prototype was cast and the tests were repeated in the same way (prototype 2016). However, there was a small change in the production technology. The mould was covered immediately after its filling by concrete and using a hot air the mould and concrete were heated. The concrete reached the temperature of about 60°C. The heating was switched off after about 3 hours. The formwork of openings was pulled out after 4 hours after filling of the mould. Then the prototype remained in the mould about 3 days. The prototype was cut again into elements P1 – P4. All four tests (identical 3 point bending tests) were executed at the age of concrete about 60 days. The tests were evaluated similarly as those of the earlier elements; the results are plotted in Fig. 5.

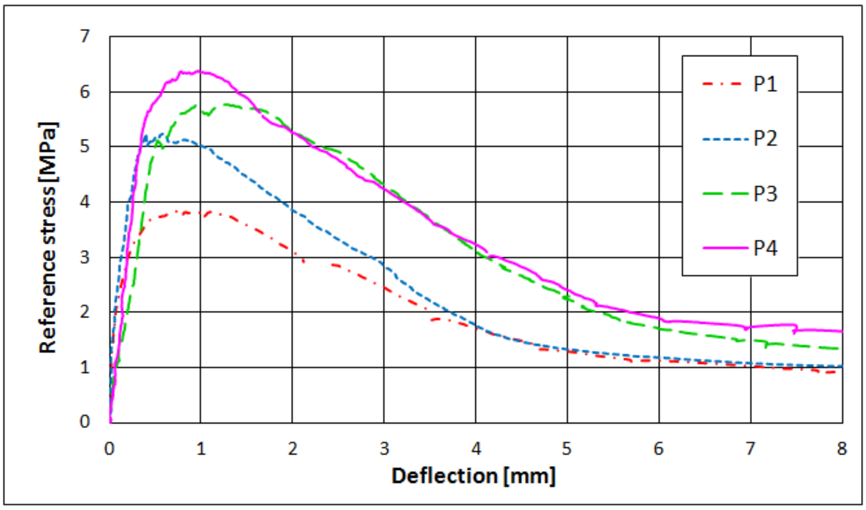

Figure 5: Reference stress in dependence on the deflection (prototype 2016)

It can be observed that again the element with the smallest thickness (P1) had minimum load carrying capacity. Increasing thickness leads to increasing load carrying capacity, although the results are recalculated so that the effects of the section thickness would be eliminated. In general the reference stress achieved in tests of the elements which were heated during setting and hardening is higher than that of the elements without heat treatment. The heating accelerated the strength development and contributed to better response of the elements.

5. ADDITIONAL TESTS OF THIN SLABS

The load carrying capacity of the elements during 3 point bending tests was not too high. It raised a question if the fibres were correctly distributed, if the model was cast in vertical position. Additional tests were prepared. Small slabs only 30 mm thick were cast in different positions – horizontal and vertical. The slabs had dimensions 800 x 800 mm. Casting of slabs is illustrated in Figs. 6 and 7. Some slabs were cut into strips 800 x 200 mm and tested in 4 point bending. Other slabs were simply supported along the perimeter and loaded by a point load in the middle of the slab.

Figure 6: Casting in the horizontal position

Figure 7: Casting in the vertical position

5.1 Strips from slabs

At the horizontally cast slabs, the direction of sawing was not specified. The slabs which were cast in vertical position were cut into strip either vertically or horizontally. The strips were subjected to 4 point bending test (Fig. 8). The span of the strips was 730 mm. The test was controlled by the deflection at the midspan. The ultimate load carrying capacity of the individual strips is summarized in the Table 4. The results completely proved that the direction of casting is important. The fibres tend to get into the horizontal position in all arrangements. The strips from horizontally cast slabs and horizontal strips from vertically cast slabs exhibited very similar results. The fibres seem to be in the direction of the span and they are able to carry the horizontal forces and thus contribute to the resistance of the sections subjected to bending. On the other hand, at the vertically cast slabs, only smaller amount of fibres remains in vertical position, which was in the direction of the span of vertical strips. It may be a reason why the load carrying capacity of vertical strips (column 4 in the Table 4) is smaller than that of other strips.

Figure 8: 4-point bending test of the slab strip

Table 4: Load carrying capacity of the strips [kN]

Strip no.	Horizontally cast slab	Vertically cast slab	
		Horizontal strips	Vertical strips
1	2	3	4
1	3.73	3.57	2.75
2	4.06	4.05	2.36
3	4.01	4.99	2.56
4	3.75	4.62	2.43
5	4.95	---	---
6	5.11	---	---
Mean v.	**4.27**	**4.31**	**2.53**
St. dev.	**0.60**	**0.62**	**0.17**

5.2 Slabs subjected to a point load

The loading scheme is illustrated in Fig. 9. The load was distributed in the middle of the slab over the circular area of the diameter of 100 or 150 mm, however, this parameter had not a significant influence on the load carrying capacity of the slab. The slabs were supported only simply without any fixation. During the loading process the corners were lifted and the supporting area was limited to the central parts of their edges. A typical failure mode is plotted in Fig.10. Very naturally two diagonal cracks were observed at all slabs.

Figure 9: Loading of the slabs

Figure 10: Typical failure mode

The load deflection diagrams of the slabs are plotted in Fig. 11. Curves H1 to H4 designate the response of slabs cast in horizontal position. Curves V1 and V2 correspond to slabs cast in vertical position. It can be observed that slabs cast in horizontal position showed larger load carrying capacity, than slabs cast in vertical position. The difference is not so significant, as it was at the strips. The fibres are partly influenced into one direction but in more complex slab performance this effect becomes not so pronounced.

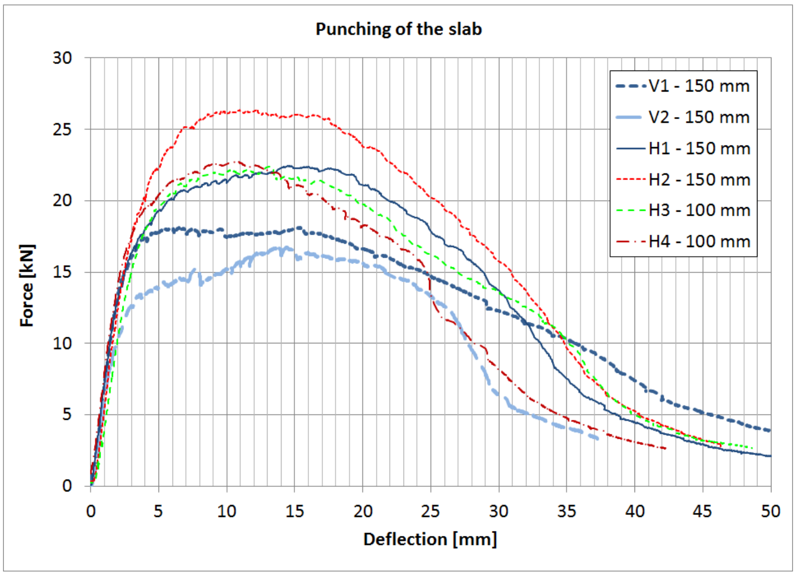

Figure 11: Load deflection diagrams of the slabs

6. CONCLUSIONS

The casting technology may significantly influence the performance of elements cast from UHPFRC. The fibres tend to get into a horizontal position at least partly, which may be a reason for non-uniform performance of structural elements. This effect was observed first on standard beams subjected to 4-point bending test. Then a similar but more significant difference was recorded on the bending tests of strips cut from thin slabs. A prototype of the hollow core slab was cast in vertical position because of better quality of surfaces and easier production. The mould can be easily filled from the top by self-compacting concrete and the cores are easy to pull out by the crane. On the other hand the tensile strength parallel to the openings may be lower. In this specific case it is not a serious problem since the slab will be in this direction prestressed. Tests on elements cut from the prototype showed that the stiff formwork may be a partial reason for microcracking and following reduction of the tensile strength. If a moderate heat treatment is used the tensile strength of UHPFRC is increased. Also a long term water storage of one element resulted in significant strength growth.

The experiments showed that it is necessary to take the casting method into account when the production technology of structural elements is designed. The actual fibre distribution, orientation and their influence on structural performance should be verified experimentally. They are dependent on the specific properties of concrete mix and flow when casting into the mould.

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