Experiments on fibre orientation in UHPC

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Abstract. Distribution and orientation of fibres in fibre reinforced composites are essential for the structural performance of elements and structures. The paper deals with experimental research where this phenomenon was investigated. During construction of the first large footbridge, many experiments were made, which should guarantee the quality of the UHPC segments. Later the problem was investigated more in detail, when a technology of hollow core slabs was developed. Three basic experiments were carried out where the direction of pouring of concrete and the structural response were compared. Standard beams which were cast in horizontal and vertical positions, small beams were cut from the hollow core slab in different directions and finally thin slabs were cast in horizontal and vertical directions and their load carrying capacity was tested. Reduction of flexural strength in different directions may vary significantly.

1. Introduction
Ultra high performance concrete is a high strength composite which tends to be widely used in concrete structures. Since the practical application requires the reinforcement of high strength cementitious matrix by fibres (steel or non ferrous) some authors use the abbreviation UHPFRC. The fibres should guarantee that the brittleness of the composite will be limited, and that the material will be able to carry a tensile force also after cracking. It is generally expected that the fibres are distributed uniformly in the material, which is understood that they are oriented in space uniformly and also that the number of fibres is similar in individual sections of the structural element. However, the experience from the production showed that the fibres are not distributed uniformly; their orientation is dependent on the way of production. If a self-compacting UHPC is used, which is quite often, the fibres tend to find their location in dependence on the flow of concrete into the formwork. The paper deals with some experiments which show the differences in the behaviour of structural elements in dependence on their production.

2. Footbridge in Čelákovice
The footbridge over the Labe River in Čelákovice was the first large structure, where the load carrying structure was made from UHPC in the Czech Republic [1]. The UHPC was produced from local materials. Its compressive strength was about 150 MPa. The cable stayed bridge still has the largest span of the cable stayed structure in the Czech Republic (156 m) and it is shown in Figure 1. The bridge deck (3 m wide) is made of segments which have two longitudinal beams which are connected.
by a thin slab (only 60 mm deep) reinforced by ribs in the distance of about 1 m. The slab has not any reinforcement with exception of fibres. At the time of production of segments (2013), there were executed many tests [2] in order to develop a reliable way of casting of individual segments so that the fibres would be distributed uniformly. The distribution of fibres was checked on segments which were cut and the fibres were observed on the cut surfaces. The distribution appeared to be rather uniform (Figure 2). The structural performance was verified by mechanical tests. The load carrying capacity of the slab was tested by a point load acting on the produced segment. The results were rather surprising; the load carrying capacity was significantly higher than that expected. The load carrying capacity in punching of the slab 60 mm thick was 350 kN (average from 4 tests). The distribution of fibres was observed on the slab after the punching test, and the fibres can be seen in all the area subjected to fracture (Figure 3).

Figure 1. Completed footbridge over the Labe River in Čelákovice.

Figure 2. Distribution of fibres in the top part of the longitudinal beam.

Figure 3. Opening in the slab after the punching test.

Tests executed prior the construction and during the construction of the footbridge brought valuable information and also proved that the applied UHPC and the technology of casting were suitable and reliable. It was also shown that it would be difficult to guarantee the quality of the footbridge without the executed tests. Some tests showed that there are some reserves, and some
dimensions could be even smaller. However, the completely new material was applied and a conservative approach to the design was desirable. The experience after almost 3 years of the footbridge operation exhibits that the accepted decisions were correct.

3. Hollow core slabs

Hollow core slabs were designed as a convenient part of different structures. The slabs which were tested were 300 mm thick and had triangular openings. The segments are assumed to be 2 m long, and casting in vertical position was proposed, in order to get all surfaces of a very high quality. In order to verify the structural performance of the slabs and also a production technology, models of the hollow core slab were produced. The dimensions of the models were 1.5 x 2.0 x 0.3 m, i.e. the thickness and the length of the model were identical to the dimensions of the segment, the width of the model was smaller (Figure 4). During the production, it was verified that the segments can be successfully produced and the formwork of the openings can be reliably removed after several hours after casting. This time is dependent on the curing of concrete. If UHPC is cured at normal conditions, the formwork of the internal openings may be pulled out after 6 hours, if heating of the segment is used, then the time can be reduced to 4 hours. At any case it is possible to produce one segment per day in one mould.

Figure 4. Model of a hollow core slab.

If a thin slab is cast in horizontal position, most of the fibres are usually oriented in horizontal position. Casting of the segment in vertical position indicates a question what is the orientation of fibres in top and bottom slab and partitions between the openings in the model of a hollow core slab, which are rather thin – about 30 to 45 mm.

The models were tested in bending in longitudinal and in transversal directions. Since no reinforcement or prestressing was applied the load carrying capacity of the models was determined by the tensile properties of UHPC. The UHPC was reinforced with high strength steel fibres. The amount of fibres was 2%. The testing is rather expensive; therefore the models were cut into smaller specimens which were subjected to loading tests. The compressive and tensile strengths were determined from laboratory tests executed on cubes, cylinders and beams. Also the tests in direct tension were executed on small cylindrical cores (Ø60 mm and length 120 mm). The flexural strength was measured on two kinds of beams. The beams (150 x 150 x 700 mm) were cast 1. in the horizontal position and 2. in the vertical position. The loading scheme was the same, 4 point bending test (span 600 mm) with two point loads located in the distance of 200 mm. The beams cast in horizontal position exhibited larger flexural strength. Basic material parameters are summarized in the Table 1.

The fibre orientation in the flanges of hollow core slabs was investigated. Small beams of dimensions 40 x 40 x 160 mm were cut from the model of the hollow core slab. The beams were cut in
the horizontal and vertical directions and also in the inclined direction of 45° with respect to the direction of casting.

Table 1. Material parameters of the applied UHPC.

| Parameter                                              | Mean value | Coeff. of variation [%] |
|--------------------------------------------------------|------------|-------------------------|
| Compressive strength – cylinders ∅150 mm x 300 mm [MPa] | 140        | 3.9                     |
| Flexural strength – beams cast in horizontal position [MPa] | 15.8       | 4.8                     |
| Flexural strength – beams cast in vertical position [MPa] | 13.8       | 4.7                     |
| Direct tensile strength – cores ∅60 mm x 120 mm [MPa]  | 4.8        | 12.4                    |
| Modulus of elasticity [GPa]                            | 46.3       | 0.9                     |

The beams were subjected to 3 point bending test (Figure 5 – span 100 mm) and the results were compared. The measured flexural strengths of the beams cut from the experimental model are described in the Table 2. The results of 6 beams cut in each direction and tested in 3 point bending test, clearly identify that the direction of casting is rather important. The bending strength of the small beams cut in the direction parallel with the openings (i.e. vertical direction when compared to the direction of casting), is rather small (13.3 MPa) and the scatter is large. The beams cut in horizontal direction (with respect to the direction of casting) exhibited higher flexural strength (19.9 MPa). It was interesting, that the beams cut in the direction 45° showed the highest flexural strength (22.7 MPa) as well as the smallest scatter.

Figure 5. Small beams cut from the hollow core slab – 3 point bending test.

Table 2. Flexural strength of the small beams.

| Spec. No. | Flexural strength [MPa] | Inclined 45° |
|-----------|-------------------------|--------------|
|           | Parallel | Perpendicular |               |
| 1         | 18.6     | 22.6          | 20.9          |
| 2         | 9.4      | 17.9          | 24.8          |
| 3         | 16.2     | 15.8          | 24.5          |
| 4         | 18.0     | 25.9          | 21.6          |
| 5         | 8.6      | 19.6          | 26.5          |
| 6         | 8.8      | 17.6          | 17.8          |
| Mean value | **13.28** | **19.90**    | **22.68**    |

Relative mean value [%] 66 100 114
Coeff. of variation [%] 36 19 14
4. Tests on thin slabs
Small slabs only 30 mm thick were cast in different positions, in a horizontal position and in a vertical position. The slabs had dimensions 800 x 800 mm. 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.

4.1. 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 strips either vertically or horizontally. The strips were subjected to 4 point bending test. The span of the strips was 730 mm (Figure 6).

![Figure 6. 4-point bending test of the slab strip.](image)

Table 3. Load carrying capacity of the strips [kN].

| Strip no. | Horizontally cast slab |  | Vertically cast slab |  |  |
|-----------|------------------------|---|----------------------|---|---|
|           |                        | 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 value 4.27 4.31 2.53

Relative mean value [%] 100 101 59

Coeff. of variation [%] 14.2 14.6 6.8

The tests were controlled by the deflection at the midspan. The ultimate load carrying capacity of the individual strips is summarized in the Table 3. 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 remained 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 3) is smaller than that of other strips. However, it is rather strange, that the coefficient of variation is significantly smaller than that at horizontally cast slabs.

5. Conclusions
The casting technology has an effect on the fibre distribution in structural elements. The fibres tend to occupy rather the horizontal position than the vertical position related to the casting direction. This phenomenon was observed on different elements. The experiments showed that in vertical direction the flexural strength can drop to 60% of that in horizontal direction (with respect to the pouring of concrete). In case of the hollow core slab the highest strength was achieved in the direction of 45° (with respect to the pouring of concrete). If the effect of orientation was investigated on standard beams, the effect of fibre distribution and orientation was significantly smaller. The fibres are oriented specifically in dependence on the pouring of concrete and on the shape of the structural element. It can be recommended to verify the fibre distribution and orientation on actual structural elements, since the laboratory specimens or similar elements need not provide a realistic figure on the fibre efficiency.

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