SHEAR TESTS ON SFR-UHPC I-SHAPED BEAMS WITH OR WITHOUT WEB OPENINGS

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This paper presents the experimentally obtained shear behaviour of SFR-UHPC (steel fibre-reinforced ultra-high performance concrete) I-shaped beams with or without web openings. To investigate the shear capacity of the beams, two times 5 I-shaped beams were tested up to failure. A mix between short straight fibres and long hooked fibres has been chosen to ensure the best contribution to the shear resistance of the beams. Test parameters included the shear span to depth ratio, the partial replacement of shear links, the presence of a web opening and the variability between identical test specimens... Results demonstrate the feasibility of this novel type of I-shaped beams.

Keywords: shear capacity, web openings, UHPC, steel fibre, FRC

1 Introduction

The use of SFR-UHPC (steel fibre reinforced ultra-high performance concrete) has gained interest during the last years in relation to more advanced structural applications [1], such as the shear resistance of reinforced concrete beams.

Alternative methods have been found in order to avoid the time consuming process of assembling stirrups (shear links) for reinforced concrete beams. In several cases [2-10], an effective solution was found to be the use of fibre reinforced concrete. With an appropriate fibre dosage and the possible use of ultra-high performance concrete, it is proven that traditional reinforcement can be replaced or reduced. In case of a total replacement, as the concrete cover for the stirrups is not needed anymore, the thickness of the web can be reduced. Especially the combination of steel fibre and ultra–high performance concrete is of interest, as SFR-UHPC is a concrete mix with superior properties compared to conventional concrete [11]: a compressive strength higher than 150 N/mm^2, higher tensile strength, a non-brittle behaviour and a low water binder ratio. Combining these aspects new structural solutions can be achieved.

2 Experimental program

Test specimens

To investigate the shear capacity of the fibre reinforced concrete beams, two times 5 I-shaped beams casted with SFR-UHPC were tested in shear until failure.

The testing elements (Figure 1) have a total length of 4000 mm, a height of 400 mm, a cross section of 140 mm width and a web thickness of 60 mm. The bottom flange has a height of 80 mm while the upper flange has a height of 60 mm.

In order to assure a shear failure, a high amount of longitudinal rebars was placed, 3 rebars of diameters 22 mm, corresponding to a geometrical reinforcement ratio of 3.16%. For the beams with a single diagonal shear link the used rebars have a diameter of 12 mm, inclined at 45°. While stirrups with a diameter of 8 mm, placed each 100 mm, were used for the beam type with vertical shear links. To anchor the longitudinal reinforcement at the beam ends, one transverse rebar of 10 mm diameter is welded to the longitudinal rebars. Each type of beam was manufactured in identical pairs and had the same SFR-UHPC composition.

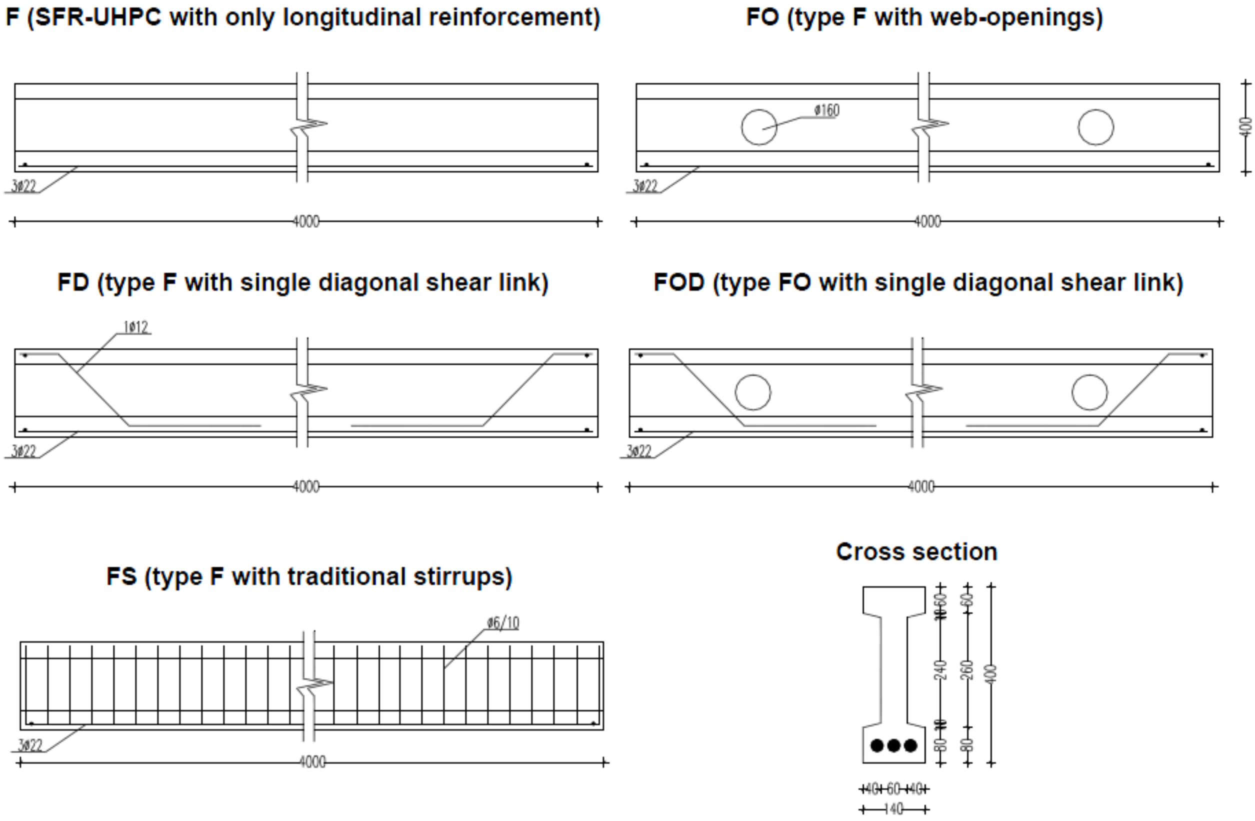

Figure 1. Schematic of beam configuration (dimensions in mm)

Test set-up

All the beams were tested in shear according to the test set-up outlined in Figure 2. Hereby the position of the supports has been chosen to test the specimens at two opposite beam ends and for two different a/d ratios. A hinge and roller support were used to avoid horizontal constrain of the beam. The load was applied on a metal plate with a spherical hinge, and between the jack and the beam a loading cell with an accuracy of 0.3 kN was placed. In this way the load is applied on a load path of 260 mm diameter. The five different types of beam, their designation and test paramters are given in Table 1.

Table 1. Test matrix

Test designation	a/d	Web openings (mm)	Diagonal shear link (mm)	Stirrups (mm)
F_25.1 and F_25.2	2.5	-	-	-
F_23.1 and F_23.2	2.3	-	-	-
FO_25.1 and FO_25.2	2.5	ϕ160	-	-
FO_23.1 and FO_23.2	2.3	ϕ160	-	-
FD_25.1 and FD_25.2	2.5	-	ϕ12	-
FD_23.1 and FD_23.2	2.3	-	ϕ12	-
FOD_25.1 and FOD_25.2	2.5	ϕ160	ϕ12	-
FOD_23.1 and FOD_23.2	2.3	ϕ160	ϕ12	-
FS_25.1 and FS_25.2	2.5	-	-	ϕ8 @ 100 mm

Beams F_25, FD_25, FO_25, FOD_25 were tested with a span of 2.73 m and a shear span to depth ratio a/d=2.5 and beams F_23, FD_23, FO_23 and FOD_23 were tested in the opposite shear span, with a span length of 2.53 m and a ratio a/d=2.3.

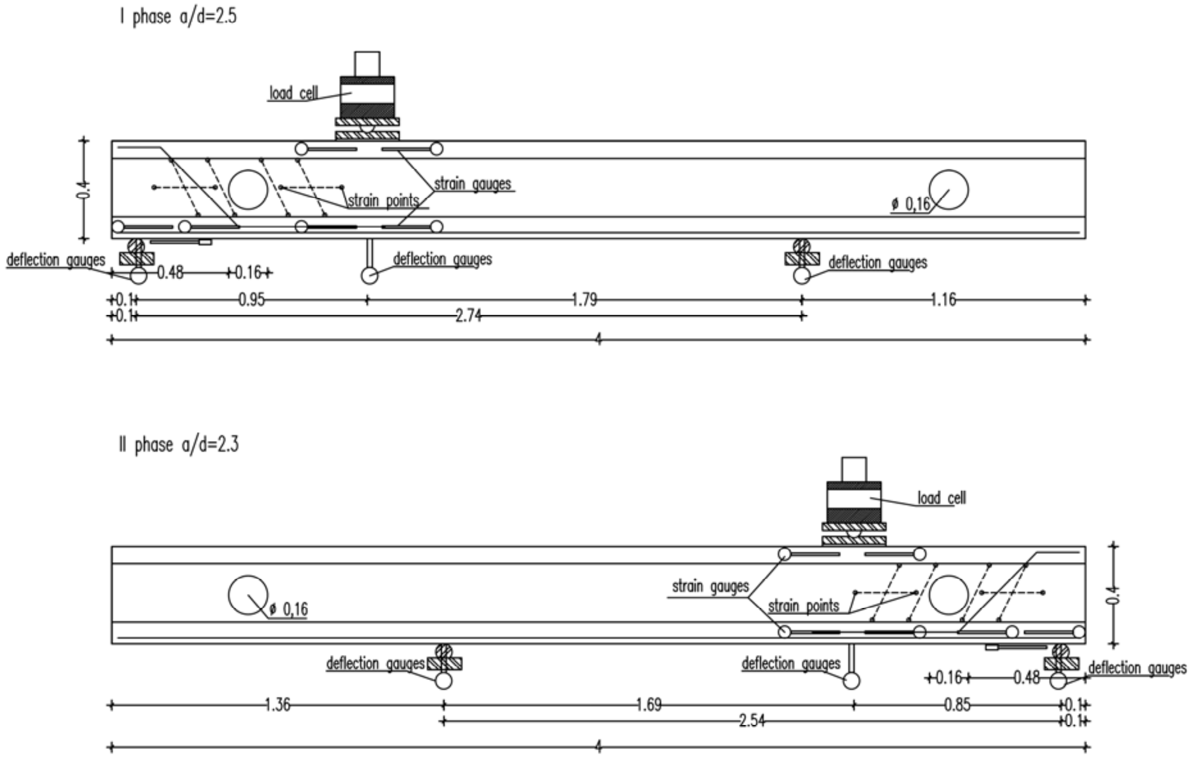

Figure 2. Test scheme and instrumentation of the beams (dimensions in m)

1The load was gradually increased until failure, using load steps of 10 or 20 kN. During the

The load was gradually increased until failure, using load steps of 10 or 20 kN. During the tests at each load level, the following manual measurements were conducted. The vertical deflection was measured with displacement transducers, while concrete strains were measured with digital gauges and an Hugenberger deformeter. Crack evolution was recorded at every loading step in terms of crack appearance and crack widths.

Strain readings of the diagonal shear links has been conducted by means of strain gauges installed at mid-height. To monitor the strains of the longitudinal reinforcement, a digital gauge was fixed on it.

Materials

The SFR-UHPC mix is based on research conducted at RWTH-Aachen University [4] and it has been optimised in order to allow the use of local constituent materials.

The amount of fibres was chosen based on [12] and it was a total amount of 78.5kg for 1 m^3 of concrete. The used fibres are a mix of 1/3 from the total quantity of short fibres of 9 mm, straight, and 2/3 long fibres with length of 25 mm, hooked. For further details on the final mix design reference is made to [13].

The concrete casting was done in a precast concrete plant in Romania. All the elements were casted in 2 batches, 5 beams per batch. A good dispersion of fibres has been assured by adding fibres at the beginning of the mixing process together with the andesite aggregates.

To determine the concrete properties compressive strength ($f_{cm,cube}$), Young's modulus (E_c), splitting tensile strength ($f_{ctm,sp}$) and bending tensile strength ($f_{ctm,fl}$), cubes with side length of 100 mm and prisms of 100 mm x 100 mm x 300 mm and 100 mm x 100 mm x 450 mm were produced. The quality control specimens were tested at 7 days, 28 days, age of beam testing and after 128 days. The obtained properties of the hardened concrete are reported in Table 2.

The values represent the mean value of each time 3 control specimens, as well as the overall average and standard deviation of the 2 batches together.

Table 2. Concrete properties

Batch	$f_{cm,cube}$ 7 days N/mm²	28 days N/mm²	testing day N/mm²	128 days N/mm²	$f_{ctm,sp}$ testing day N/mm²	E_c testing day N/mm²
1	85.7	141.6	135.1	159.5	12.2	43470
2	80.6	135.9	140.0	146.3	12.2	43005
Average	83.2	138.8	137.6	152.9	12.2	43237.5
St. dev.	3.6	4.0	3.5	9.3	0.0	328.8

3 Test results and discussion

For the post cracking behaviour of the SFR-UHPC, crack opening controlled bending tests have been performed. For these tests, prisms of 100 mm x 100 mm x 450 mm (first batch) and 100 mm x 100 mm x 300 mm (second batch) were tested tuntil failure with a span of 400 mm and 280 mm, respectively. During the tests, deflection, load and CMOD (crack mouth opening displacement) were recorded. The post-cracking behaviour of the SFR-UHPC can be further represented by considering the bending tensile strength of the maximum load (fctm,fl), as well as the residual bending tensile strength fRm,1 till fRm,4. The values are given in and represent the mean value of 3 CMOD specimens per batch, as well as the overall average and standard deviation of all specimens (Table 3).

Table 3. SFR-UHPC properties from bending tests at 128 days

Batch	$f_{ctm,fl}$ [MPa]	$f_{Rm,1}$ [MPa]	$f_{Rm,2}$ [MPa]	$f_{Rm,3}$ [MPa]	$f_{Rm,4}$ [MPa]
1	12.66	11.38	6.28	4.15	3.06
2	12.32	11.96	6.57	4.55	3.20
Average	12.49	11.67	6.43	4.35	3.13
St.dev. between batches	0.24	0.41	0.20	0.28	0.09

The main test results are summarized in Table 4 in terms of shear capacity (V_{exp}) of each beam, ratio of obtained shear strength with respect to the considered reference situation of beam type F_25 (no additional shear links, no web opening, a/d = 2.5), and failure aspect. For each beam, first cracking occurred due to bending under the point load at a value less than 10% of the ultimate load.

Eventually, shear cracks occurred at about 36 % to 93 % of the ultimate load, and all tested elements failed in shear. In the beams with diagonal rebars, the shear link has been broken.

The load-deflection behaviour of the beams is represented in Figure 3 and Figure 4.

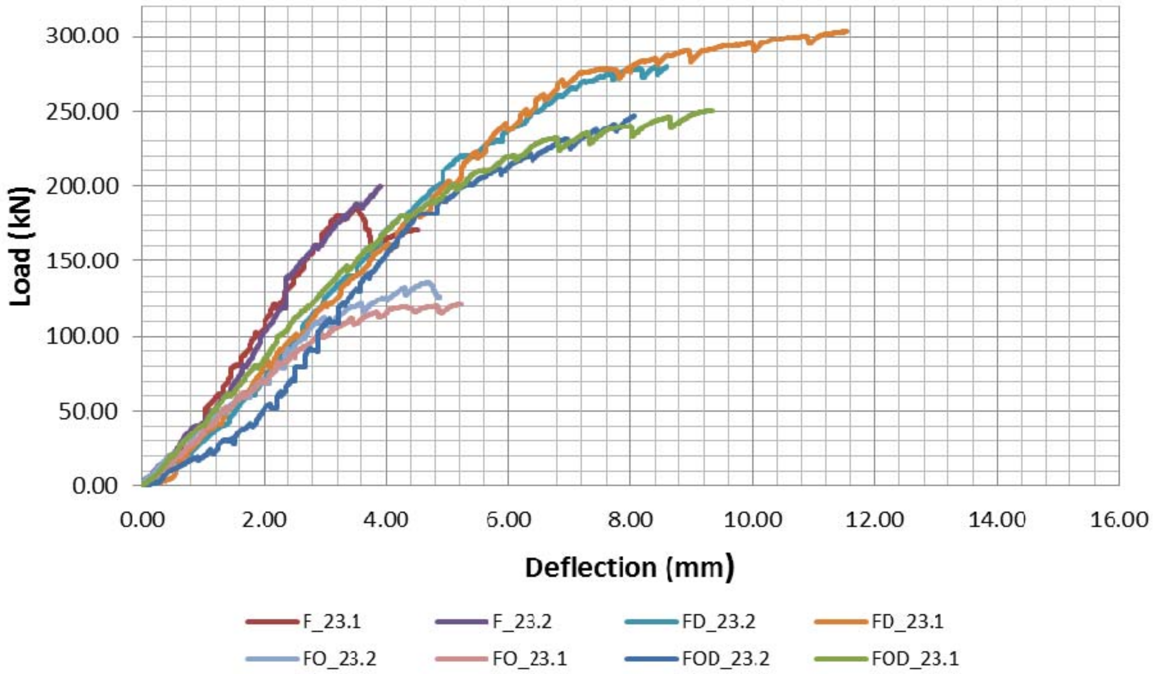

Figure 3. Load-deflection diagram for tested beams at a/d=2.3

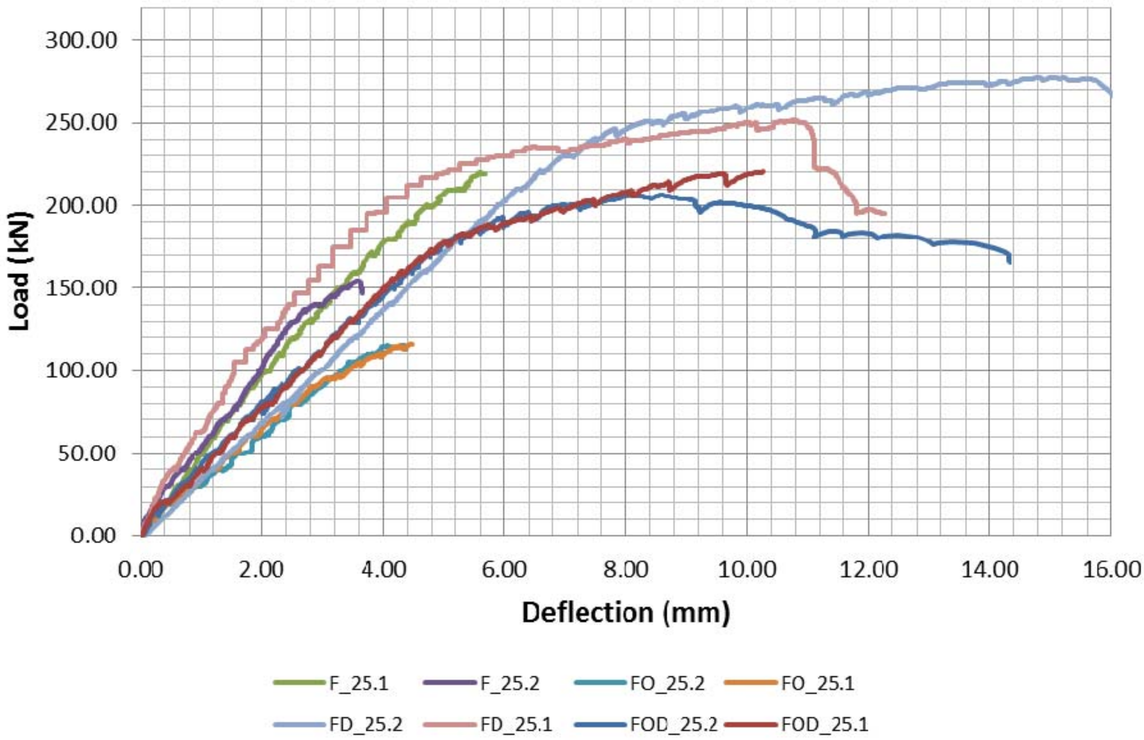

Figure 4. Load-deflection diagram for tested beams at a/d=2.5

From the obtained test results in can be observed that the introduction of the web openings reduced the shear capacity with up to 40%. By introducing a single shear link of 45° in beams with web openings, the shear capacity increased beyond that of the reference SFR-UHPC beams (without web openings and shear links).

For beams without web opening and depending on the required level of shear capacity the use of SFR-UHPC is feasible without or with the introduction of extra shear links. For the tested configurations, additional shear capacity of 32% to 56% was obtained by adding a limited number of stirrups. Hereby, a higher effect was obtained for the beams tested with the shortest shear span (a/d = 2.3). For a further discussion on the obtained test results reference is made to [13].

Table 4. Shear capacity of the beams

	$V_{exp.1}$ (kN)	$V_{exp.2}$ (kN)	V_{exp} (kN)	V_{exp}/ $V_{exp.F}$	Failure aspect
F_25	149	93	121	1.00	s
FD_25	152	168	160	1.32	s
FO_25	70	70	70	0.58	s
FOD_25	133	125	129	1.06	s
FS_25	168	199	184	1.52	Not completely failed
F_23	114	123	119	0.98	s
FD_23	206	172	189	1.56	s
FO_23	75	85	80	0.66	s
FOD_23	154	154	154	1.27	s

The shear cracks have been observed to form as an extension of the flexural cracks, which bent over. When the shear cracks opened the sound of fibres being pulled out and failing was observed. The additional shear was carried by the concrete in the compression zone and by the dowel action.

4 Conclusion

A total of ten I-shaped beams were tested to investigate the shear behaviour of SFR-UHPC beams, including the influence of web-openings, single diagonal shear links and stirrups on the mechanical behaviour of these elements. From the results of this study the following conclusions can be drawn:

All the tested beams, except those with both stirrups and steel fibres, showed a shear tension failure through the web.

It was observed that all the beams with single diagonal shear link collapse at more than 50% higher load, compared to the equivalent beams with only longitudinal reinforcement. As all beams have the same amount of fibres, the higher failure load relates to the additional shear link. In general, beams with higher shear span/ depth ratio fail at a lower shear capacity.

The shear resistance of the beams with web-openings was about 62% of the reference beams (type F), while for beams with web-openings and a single diagonal shear link (type FOD) the resistance was about 80% of the beams with single diagonal shear link (type FD). The use of the fibres and diagonal reinforcement adds strength and ductility requirements.

The conducted experimental work confirms the feasibility of SFR-UHPC for I-shaped reinforced concrete beams and replacing classical stirrups by fibre reinforced concrete, with or without the combination of a single diagonal rebar as additional shear link.

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