

# Shear Behaviour of UHPC Beams with Varying Degrees of Fibre and Shear Reinforcement

Norbert Randl<sup>(✉)</sup>, Tamás Mészöly, and Peter Harsányi

Carinthia University of Applied Sciences, Villacherstr. 1,  
9800 Spittal/Drau, Austria  
n.randl@cuas.at

**Abstract.** An experimental campaign was conducted to investigate the behaviour of I-shaped single span beams made of Ultra-High Performance Concrete (UHPC) subjected to shear loading. The main parameters were the fibre content (up to 2% by volume) and the degree of stirrup reinforcement (no stirrups or with stirrups diameter 10 mm, spacing 125 to 300 mm). A total of 18 tests were performed, all of them ending up in typical shear failure: Pronounced shear cracks formed along the web between support and load introduction at around a level of 60–70% of the ultimate load. Close to the maximum load level, the formation of a critical main shear crack with an average inclination of about 30° to 35° was observed, finally propagating into the compressed upper flange sections. The effect of the fibres as well as the stirrup contribution are assessed and quantified. Thereby a decisive effect of the fibres was observed: The addition of 1% to 2% fibres by volume led to a more distributed crack pattern as well as a significant increase of the ultimate load, rather proportional to the residual tensile strength than to the fibre content. The effect of adding fibres was larger for non shear-reinforced beams than for beams provided with stirrups.

**Keywords:** UHPC · Shear design · Fibres · Stirrup reinforcement

## 1 Introduction

Due to the complex failure process and the different contributing and interacting mechanisms, the behaviour of reinforced concrete (RC) structures in shear is still in the focus of research. The recently elaborated design approach of Model Code 2010 (*fib* 2012) is mainly based on the Modified Compression Field Theory and a kind of “stress field approach” for shear reinforced members (Sigrist et al. 2013). On the other hand, Eurocode 2 (DIN EN 1992-1-1 2011) design equations have an empirical background for non-shear reinforced members and represent the truss analogy for members with stirrup reinforcement. Taking this into account, it becomes evident that the behaviour of fibre-reinforced Ultra-High Performance Concrete (UHPC) is even less known due to additional factors such as the effect of steel fibres and particular shear slip/aggregate interlocking behaviour along crack surfaces.

Up to now there are only few studies available that focus on the shear behaviour of steel fibre-reinforced UHPC-members. Thiemicke and Fehling (2016) did tests on the

shear behaviour of fibre-reinforced I-shaped UHPC beams with a maximum fibre content of 1 Vol.-%. Bertram (2012) investigated prestressed UHPC beams and developed a model based on the addition of the various contributing effects, taking into account the inclination of the upper and lower chords and their own stiffness in shear. The kind of additive approach is in principle similar to existing models for predicting the shear load bearing capacity of steel fibre-reinforced members made of normal strength concrete. Also the AFGC guideline (AFGC 2013) presents an additive approach, which delivers conservative results according to Baby et al. (2010).

## 2 Test Setup

A total of 18 UHPC beams have been tested under monotonic loading until failure in order to identify the different contributing mechanisms to the overall shear resistance. The majority of the beams were subjected to three-point bending with the geometric proportions of the test specimens as shown in Fig. 1. Only for the first two beams (B1 and B2) the test setup was a four-point bending configuration.

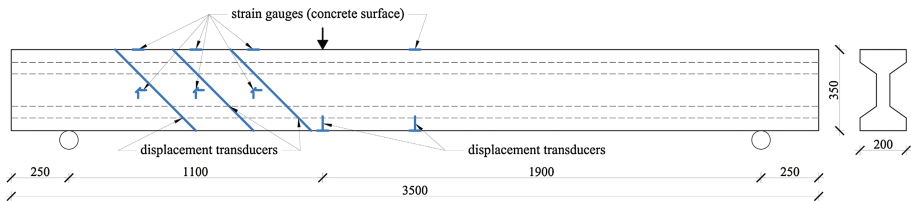


Fig. 1. Three-point test setup

All beams had a total length of 3.5 m and a single span of 3.00 m. The height of the I-shaped cross-sections was 350 mm, with a thickness of the web of 58 mm and a width of the flanges of 200 mm. The distance from load introduction to nearest support was 1.10 m for the three-point bending setup and 1.00 m for the four-point bending configuration, so that the shear-span-to-depth ratio  $a/d$  was larger than 3 (3.5 and 3.2) and thus sufficient enough to prevent direct load transfer via an inclined compression strut to the support.

Strain gauges were applied before casting on 2 or 3 stirrups each (in the case of stirrup reinforcement) at the level of the beam axis in the expected centre of the compression field. Further strain gauges were glued on the longitudinal reinforcing bars between the load introduction and the support as well as in the mid cross-section of each beam on the 2 opposite sides of the according bar surface (thus allowing for evaluation of the average bar strain). In addition the strains on top of the beam in the concrete compression zone and aside the web region were recorded by means of strain gauges glued to the concrete surface.

Moreover a digital image correlation (DIC) system was applied for comprehensive supervision of local deformations and the crack formation process (crack patterns were derived from the subsequently calculated major principal strains of the DIC system

measurements). The deflections were measured by means of LVDTs at the load introduction sections and in the mid cross-section.

### 3 Material Properties

The used UHPC was a fine grain mixture with a maximum aggregate size of 0.4 mm and had been developed in previous studies (Randl and Mészöly 2015; Randl et al. 2014). It basically consists of the following 6 ingredients: Portland cement type CEM I 42.5 R HS, silica fume, quartz powder, quartz sand, superplasticizer and water. The water-to-binder ratio, taking into account a 70% water content in the superplasticizer, was 0.21. In the case of the fibre-reinforced UHPC mixtures either 1 or 2 Vol.-% of fibres were used. The added fibres were straight and smooth steel wire fibres with a nominal tensile strength of 2000 MPa. The diameter  $\phi_f = 0.2$  mm and a nominal length  $l_f$  of 15 mm result in an aspect ratio ( $l_f/\phi_f$ ) equal to 75.

The average compressive strength measured on 100 mm cubes was around 166 MPa on the 28th day and 171 MPa on the day of testing. The cubes for the 28 days compressive strength were stored and tested according to ÖNORM EN 12390. The cubes for compressive strength on the day of testing were stored under laboratory conditions. The compressive strength  $f_{cm}$  for each beam specimen at the day of testing is listed in Table 2.

In order to prevent premature bending failure, all beam specimens were provided with a strong longitudinal reinforcement at the bottom side: 7 reinforcing bars  $\phi$  20 mm were applied, using high grade steel S 900/1100 with a nominal yield strength  $R_{p0.2}$  of 900 MPa. For the stirrups traditional BSt 550 steel was used with a characteristic yield strength  $R_{yk}$  of 550 MPa. The distance of the stirrups  $\phi$  10 mm was varied between 125 mm and 300 mm (in the case of the beams with shear reinforcement).

### 4 Testing Program

Apart from some natural scattering of the concrete strength, the deliberately varied parameters were the steel fibre content (non fibre-reinforced/1 Vol.-%/2 Vol.-%) and the amount of stirrup reinforcement (no stirrups/ $\phi$ 10 at 125 mm spacing/ $\phi$ 10 at 200 mm spacing/ $\phi$ 10 at 300 mm spacing). Table 1 gives an overview of the testing program.

**Table 1.** Matrix of testing program – shear reinforcement ratio vs. fibre content

Fibre content	Stirrups $\phi$ 10			No stirrups
	$s = 125$ mm	$s = 200$ mm	$s = 300$ mm	–
	$\rho_w = 2.17\%$	$\rho_w = 1.35\%$	$\rho_w = 0.90\%$	$\rho_w = 0\%$
2 vol.-%	B1, B2	B15, B26	B17	B19, B25, B30
1 vol.-%	–	–	B28	B20, B24, B29
0 vol.-%	B22	B16	B18	B21, B23, B27

### 5 Observed Failure Mode and Load Bearing Behaviour

In all tests a pronounced shear failure mode and the formation of typical shear cracks was observed (see representative example in Fig. 2). The load displacement behaviour was significantly affected by the amount of fibres and/or stirrups: While the UHPC beams without fibres or stirrups reached a load of only 50–80 kN, the addition of fibres and/or stirrups led to much higher load bearing capacities (see discussion in the next section). Figure 3 depicts representative load displacement curves for tested beam constellations with minimum/maximum contents of fibres and/or stirrups. All curves show a decrease of stiffness at a load level in the range of 30 to 50 kN due to the formation of the bending cracks. In addition all beams with a fibre content of 2 Vol.-% are significantly stiffer compared to the other beams with less or no fibres. Adding stirrups and/or fibres led to a more ductile structural response with an increased deformation at higher ultimate loads.



Fig. 2. Failure mode of beam B29 (no stirrups, 1 Vol.-% fibres)

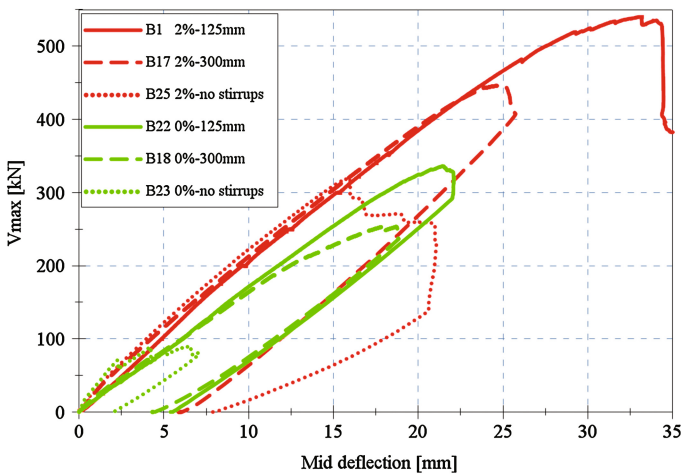


Fig. 3. Load vs. displacement curves

In the case of the non shear-reinforced UHPC beams without fibres, with the formation of a critical shear crack propagating into the concrete compression zone the maximum load was quickly reached and brittle failure was observed. In the case of the fibre-reinforced beams, a number of (rather hairline) cracks formed when the introduced force reached a level of about 30 to 50% of the ultimate load. In general a fine crack distribution due to the fibres was observed. Typically at higher load levels one to three larger cracks localized and finally opened excessively so that the beam part above the upper of the two cracks separated increasingly from the rest of the beam, accompanied by a sizzling noise from the fibre pull-out. At the point of maximum load level the main crack propagated to the compression face and spalling of concrete parts to the sides of the beam from the flange and web regions was observed. The beams reinforced with stirrups behaved similarly, with the main difference that the crack distribution was less pronounced so that at similar load levels there appeared more large inclined cracks in the web reflecting the truss effect (see Fig. 4). At ultimate stage the cracks were slightly less inclined ( $\sim 31^\circ$ ) than in the fibre-reinforced beams ( $\sim 34^\circ$ ). In stirrup reinforced beams, nearly all stirrups with applied strain gauges reached the yield strain of the steel, depending on the amount of stirrups at a load level of about 60% to 80% of the maximum load. In beams provided with both fibres and stirrups, the strains in the stirrups were lower at same load level compared to the beams with stirrups and without fibres. Also the formation of the first visible shear cracks delayed in that case. In general, all beams reinforced with fibres and/or stirrups exhibited a less brittle behaviour than the UHPC beams without.

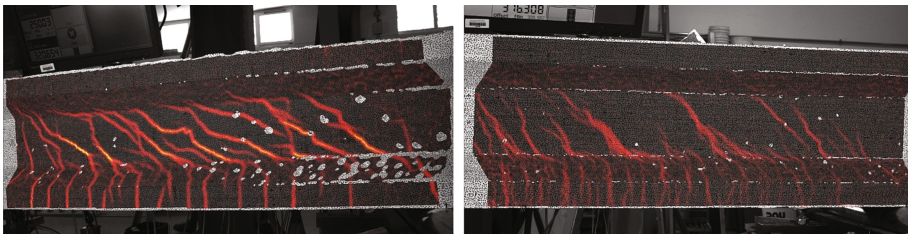


Fig. 4. Crack pattern from DIC system in beams B22 and B30 at 250 kN

## 6 Assessment of Test Results

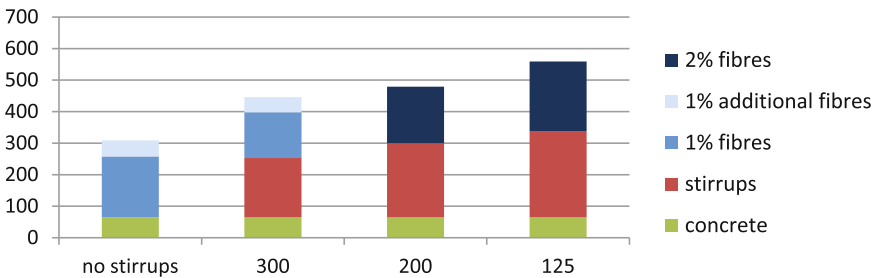
All recorded maximum loads and the respective back-calculated shear forces are listed in Table 2. A significant contribution of the fibres to the overall shear loading capacity can be clearly identified: Without stirrups, 1 Vol.-% of fibres leads to a nearly 4 times higher capacity than without (+190 kN shear load increase) and 2 Vol.-% results in a factor of around 4.75 (+240 kN shear load increase). The load gain in shear due to the fibres was, however, not proportional to the fibre content. This tendency fits to the observations made by Thiemicke and Fehling (2016). The load gain with 2 Vol.-% of fibres is similar to the effect achieved alternatively by the arrangement of stirrups

**Table 2.** UHP(FR)C compressive strength and beam failure loads

Beam No.	$f_{cm}$ (N/mm <sup>2</sup> )	stirrups $s$ (mm)	fibres (Vol.-%)	$F_{max}$ (kN)	$V_{max}$ (kN)	$V_{max}^a$ , average (kN)
B1	185.2	125	2	1080	540	559
B2	184.2	125	2	1155	578	
B22	154.3	125	0	532	337	337
B15	169.7	200	2	700	443	479
B26	162.8	200	2	814	516	
B16	168.2	200	0	474	300	300
B17	170.4	300	2	704	446	446
B28	165.6	300	1	628	398	398
B18	174.9	300	0	400	253	253
B19	160.4	–	2	397	251	309
B25	188.4	–	2	504	319	
B30	177.5	–	2	564	357	
B20	161.9	–	1	419	266	258
B24	174.8	–	1	314	199	
B29	186.5	–	1	487	308	
B21	160.8	–	0	130	83	65
B23	169.6	–	0	98	62	
B27	166.6	–	0	79	50	

<sup>a</sup>: Average value for same Vol.-% of fibres and amount of stirrups

ø 10 mm at a distance of 200 mm, however associated with larger deflections. In order to illustrate the average contributions and load gains, the results are also presented in graphical form in Fig. 5.



**Fig. 5.** Comparison of contributions to shear resistance for 18 beams (horizontal axis: stirrup distance; vertical axis: maximum shear load [kN])

When stirrups were provided, the effect of the fibres was smaller than without stirrups but still significant: independent from the stirrup amount, an average increase of shear strength of around +200 kN was recorded when changing from 0 Vol.-% to

2 Vol.-% of fibres. On the other hand, the shear strength gain due to an enhancement of the number of stirrups seems not strongly affected by the fibre amount according to the test results: changing the stirrup distance from 300 mm to 125 mm led to a shear load gain of roughly +90 kN without and about +110 kN with 2 Vol.-% of fibres. Moreover it can be seen that the increase of shear resistance due to stirrups was larger for beams without fibres and less for beams with fibres (Fig. 5).

Based on the AFGC guideline (AFGC 2013) the shear resistance was calculated for each tested beam in order to compare the approach as per (AFGC 2013) to the test results. The calculation was based on the application of mean values of the material properties and performed with the measured real dimensions of the specimens. The inclination angle of the compression struts was derived from the tests as an average value in each shear region. Hence in the calculation an angle of  $34^\circ$  for beams without fibres,  $33^\circ$  for beams with 1 Vol.-% and  $31^\circ$  for beams with 2 Vol.-% of fibres was used.

The residual tensile strength ( $\sigma_{R,f}$ ) required for the derivation of the fibre contribution was determined on the basis of flexural tests on prisms  $150 \times 150 \times 700$  mm. The  $\sigma_{R,f}$  values were back-calculated via an inverse analysis according to the AFGC guideline (AFGC 2013) from the tensile stress vs. crack width curves with an ultimate crack width ( $w_u$ ) value of 0.5 mm, resulting in a value of 5.0 MPa for beams with 1 Vol.-% and 6.3 MPa for beams with 2 Vol.-% of fibres. Detailed information about the derivation of the  $\sigma_{R,f}$  values is given in Randl and Meszöly (2015).

The ratios of measured vs. calculated shear resistance values lead to the conclusion that the AFGC calculation is on average about 15–20% on the conservative side. However, with higher amounts of shear reinforcement the predicted value was close to the maximum shear force from the test. The calculated value was only once slightly higher than the measured one. Without stirrups or with a low degree of shear reinforcement the ratios of the calculated shear forces vs. the measured ones were close to 0.7. Taking all test results of the present experimental campaign into account, the shear design approach as per (AFGC 2013) slightly overestimates the contribution of the stirrups and somewhat underestimates the contribution of the fibres. On average, the AFGC approach was on the conservative side when evaluating the present tests.

## 7 Conclusions

A total of 18 UHP(FR)C beams reinforced in longitudinal direction with high grade steel bars were tested in shear. All tests ended up with a pronounced shear failure. The two major goals of the test series were the investigation of the shear behaviour of UHP (FR)C beams in general and the determination of the specific effects of fibres, concrete and stirrups on the maximum shear capacity. Therefore the ratios of shear reinforcement and fibre content were varied, resulting in 10 different types of beams. The analysis of the test results led to the following conclusions:

- In general yielding of the stirrups was observed, initiating at 60% to 80% of the ultimate load depending on the stirrup distance.

- For an ordinarily shear reinforced beam the increase of the number of stirrups had less effect on the maximum shear capacity than adding 1 or 2 Vol.-% of fibres.
- The effect of fibres on the shear resistance was significant and quite proportional to the residual tensile strength. The impact of adding fibres was larger for a non shear-reinforced beam than for beams with stirrups.
- The tested beams with steel fibres behaved stiffer and also less brittle than the same type of beams without fibres.
- With increasing fibre content, a finer crack distribution was generally observed.
- The observed shear cracks in beams with no fibres (0 Vol.-%:  $\sim 34^\circ$ ) were slightly steeper than in fibre-reinforced beams (1 Vol.-%:  $\sim 33^\circ$  and 2 Vol.-%:  $\sim 31^\circ$ ).
- The test results were compared to the currently available shear design approach of the French AFGC guideline (AFGC 2013). The AFGC design approach in general allows for a quite realistic prediction of the shear load bearing capacity. It leads to rather conservative results, on average about 15 to 20% on the safe side in the present study.

**Acknowledgements.** The funding of this research by the Austrian Research Promotion Agency (FFG) is gratefully acknowledged.

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