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Shear behavior of fiber-reinforced ultra-high performance concrete beams

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ABSTRACT

Twenty I-shaped beams made of ultra-high performance concrete (UHPC) with different steel fiber content (up to 2% by volume) and with varying degrees of shear reinforcement (no stirrups or with diameter 10 mm stirrup, 125–300 mm spacing) were tested in shear. The mean compressive strength of the concrete was around 170 MPa. All tests failed in shear. The study investigated the effect of the traditional transverse shear reinforcement and the effect of the fiber reinforcement on the shear behavior as well as the interaction of both parameters, considering the failure mechanisms and the shear capacity. The cracking process was monitored by a digital image correlation (DIC) measurement system and the results of the evaluation are presented. The measured ultimate shear capacity of the different setups was compared to the current AFGC design approach.

1. Introduction

The behavior of reinforced concrete (RC) structures in shear is still an intensively investigated field of research, and in the last decades several advanced models and design approaches have been developed [1–5]. The current design approach of Model Code 2010 [6] is mainly based on the Simplified Modified Compression Field Theory (SMCFT) and the "stress field approach" for shear reinforced members [7]. Eurocode 2 shear design for members without shear reinforcement [8] is partly based on an empirical background. The approach for members with shear reinforcement represents the truss analogy.

The shear behavior of fiber-reinforced ultra-high performance concrete is even less known due to additional factors such as the effect of steel fibers and in particular shear slip and aggregate interlocking behavior along crack surfaces. Only a few studies are available that focus on the shear behavior of steel fiber-reinforced UHPC members. Graybeal [9] carried out three shear tests with prestressed UHPC I-shaped beams without shear reinforcement, and according to his study, prediction of most code provisions significantly underestimate the shear capacity of these beams. Wu and Han [10] tested eleven reinforced concrete I-beams without shear reinforcement, eight of which failed in shear. The main variables were fiber volume content, flexural reinforcement ratio, section type, and span to depth ratio. Based on the test results, a formula for the initial diagonal cracking load was developed. The authors concluded that the conventional equations to quantify shear strength are not appropriate and developed an analytical model. Fehling, Bunje and Leutbecher [11] investigated rectangular beams made of fiber-reinforced UHPC without shear reinforcement and rectangular UHPC beams without fiber and shear reinforcement. The experimental results were in good agreement with the shear design approach of EN 1992-1-1 [8] and with the shear model by Zink [12] for beams without shear and fiber reinforcement. However, results of beams from fiber-reinforced UHPC without shear reinforcement showed much higher shear capacity. Only beams with a very high longitudinal reinforcement ratio ended up in shear failure. Voo, Poon and Foster [13] tested eight prestressed fiber-reinforced UHPC beams without stirrups in shear. In these tests the shear-to-depth ratio, as well as the quantity and type of steel fibers were varied. The results of the tests were compared to values derived from a plastic shear model, and the authors found good correlation with the experimental results. Thiemicke and Fehling [14,15] investigated UHPC beams with a pronounced I-shaped cross-section in the shear zone with and without shear reinforcement and with a maximum fiber content of 1 vol%. Their results showed that the fiber reinforcement can significantly change the shear behavior and increase the shear capacity. They proposed a calculation model to predict the shear-bearing capacity of fiber-reinforced UHPC beams. Bertram and Hegger [16–18] investigated the shear behavior and mechanisms of prestressed UHPC beams with and without fiber reinforcement. They focused on the influence of prestressing on arching action and the effect of the fiber content and shear slenderness on shear capacity. The derived additive model takes into account the contribution of the fibers, the concrete and additional reinforcement. Lim and Hong [19] tested steel fiber-reinforced rectangular UHPC beams with and without shear reinforcement. They investigated the effects of the different amounts of fibers and shear reinforcement on the shear behavior and shear capacity, as well as the required spacing limit

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of the stirrups. Baby, Marchand and Toutlemonde [20,21] carried out an experimental program with eleven I-shaped UHPC beams, where the varying parameters were the fiber type (steel and organic), the fiber content (0, 2, 2.5 and 4.7 vol%), the amount of shear reinforcement, the concrete mixtures, the presence of prestressing and the application of heat treatment. They focused on the crack localization and the overall shear behavior together with the actual orientation of the fibers derived from sawn specimens, and identified the shear capacity taking into consideration all these influencing parameters. They used their own and several other available experimental results to evaluate the prediction of the current shear design models at serviceability limit state and also at ultimate limit state. Sato, Pansuk, den Uijl and Walraven [22] performed shear tests on UHPC beams without shear reinforcement and with different fiber content up to 1.6 vol%. They investigated the shear behavior, crack pattern and shear capacity. Recommending a formula for calculating the shear capacity based on the post-cracking tensile strength, and taking into account the higher rotation capacity, they extended the strut inclination θ to the range $1 \leq \cot\theta \leq 3$. The AFGC Recommendations [23,24] provide an additive approach for the fiber-reinforced UHPC beams with the minimum inclination θ of 30°, which delivers conservative results according to Baby et al. [25]. The present study compares this latter approach to the experimental results.

2. Experimental campaign

Twenty UHPC beams were tested under monotonic loading until failure in order to identify the different contributing mechanisms to the overall shear resistance. All beams had a total length of 3.50 m and a single span of 3.00 m. The I-shaped cross-section and the high longitudinal reinforcement ratio (5.1%) were chosen to ensure shear failure. The height of the I-shaped cross-sections was 350 mm, with a thickness of the web of 60 mm and a width of the flanges of 200 mm. While the first two beams (B1 and B2) were tested in a symmetric four-point bending configuration, eighteen other beams were subjected to an asymmetric three-point bending. The test setups and the geometric dimensions of the test specimens are shown in Fig. 1. The distance from the load introduction to the support was 1.00 m for the four-point bending configuration and the distance from the load introduction to the nearest support was 1.10 m for the three-point bending setup. The shear span to depth ratio (a/d) in both cases was larger than 3 (between 3.2 and 3.3 in the four-point configuration and between 3.5 and 3.6 in the three-point configuration), and thus sufficient to prevent significant direct load transfer to the support via an inclined strut [26,27].

Figs. 1 and 2 show the applied measurement devices. At two or three stirrups (in the case of shear reinforcement) the tensile strain of the vertical legs was measured by pairs of strain gauges applied to the stirrups before casting. The positions of the strain gauges were at the level of the beam axis in the expected center of the compression field in the shear zone. Further pairs of strain gauges were installed at the mid-longitudinal reinforcing bar between the load introduction and the support as well as in the mid cross-section of each beam. In addition, the strains on top of the beams in the concrete compression zone and the web region were recorded by means of strain gauges installed at the concrete surface (see Fig. 1). The deflections at the load introduction and in the mid cross-section were measured by means of displacement transducers. Moreover, inclined displacement transducers were used in the shear zone to measure the deformation of the beam and the formations of the shear cracks. Parallel to strain gauges and the displacement transducers, deformations were measured with a digital image correlation measurement system. A DIC system is a comprehensive tool for supervision and monitoring of global movements, local deformations and the crack formation process.

The used UHPC was a fine grain mixture with a maximum aggregate size of 0.4 mm which was developed in previous studies [28,29]. The mixture had the following ingredients: Portland cement type CEM I 42.5 R HS, quartz sand, quartz powder, silica fume, superplasticizer and water. The water to cement ratio was 0.23, the water to binder ratio, taking into account a 70% water content in the superplasticizer, was 0.21. In the case of the fiber-reinforced UHPC mixtures, either 1 or 2 vol % of fibers were used. The added smooth steel wire fibers were straight with a nominal tensile strength of 2000 MPa. The diameter $ø_f = 0.2$ mm and a nominal length l_f of 15 mm result in an aspect ratio ($l_f/ø_f$) equal to 75. The mean compressive strength measured on 100 mm cubes was around 166.1 MPa on the 28th day according to ÖNORM EN 12390 and 171.2 MPa on the day of testing stored under the same laboratory conditions as the beams. The mean compressive strength f_{cm} for each beam specimen at the day of testing is listed in Table 3.

In order to prevent premature bending failure, all specimens were provided with a strong longitudinal reinforcement on the tensile side: seven reinforcing bars with a diameter of 20 mm were applied, using high grade steel S900. Traditional B550B steel was used for the stirrups. The strength properties of the used reinforcing steel bars listed in Table 1. In the case of the beams with shear reinforcement, the distance of the stirrups with a diameter of 10 mm was varied between 125 mm and 300 mm.

In the testing program, the deliberately varied parameters were the steel fiber content (non fiber-reinforced, 1 vol% and 2 vol%) and the amount of stirrup reinforcement (no stirrups, ø10 at 125 mm spacing, ø10 at 200 mm spacing and ø10 at 300 mm spacing). Table 2 provides an overview of the experimental campaign.

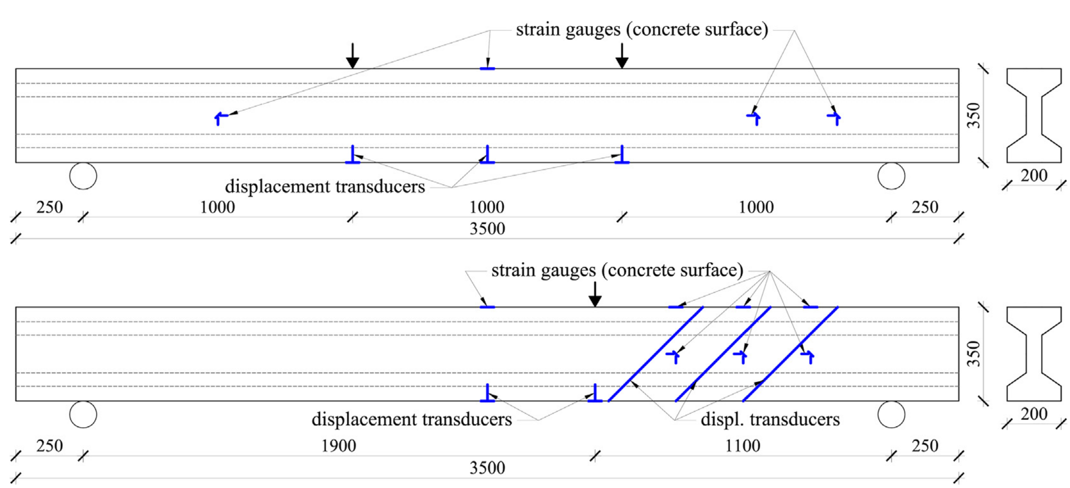

Fig. 1. Four-point and three-point test setups and external measurement devices.