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Punching strength of flat plates reinforced with UHPC and double-headed studs

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ABSTRACT

To verify the beneficial use of UHPC in the highly stressed region of column-slab connections, a total of ten punching tests on reinforced concrete slabs were performed. All interior column-slab connections included double-headed studs as shear reinforcement. Nine test specimens were in addition strengthened by fibre-reinforced Ultra High Performance Concrete (UHPC) units. These elements were built in around the columns in the slab compression zone, replacing there the normal strength concrete (NSC). UHPC units with three different diameters were applied. To allow for a flexible combination of UHPC unit and double-headed studs, most of the UHPC units were separated into four parts with joints in between and were provided with channels for the double-headed studs. The slabs including a UHPC element reached significantly higher failure loads than the test specimens without such an element. In the slabs including the UHPC units with smaller diameter, a clear punching shear failure outside the elements was observed. In the case of the larger UHPC units, significant cracks occurred inside the elements, indicating the initiation of a failure of the UHPC.

1. Introduction

Flat plates are reinforced concrete slabs, which are supported on columns. Such slabs without beams can be economically manufactured and provide good conditions for optimal use of space and further constructions (e.g. piping, ventilation ducts) without obstructions. Flat plates can either fail in flexure or in a local shear failure, the so-called punching shear failure. In tests, another type of failure is the delamination of the concrete core due to high bond stresses [1]. This failure mode is not of real practical significance, because nowadays the design codes provide appropriate detailing provisions and demand the use of deformed bars for the flexural reinforcement. To achieve an appropriate punching shear resistance at reasonable slab thicknesses, very often shear reinforcement is necessary. In the past, several types of punching shear reinforcement have been developed. The effectiveness of the punching shear reinforcement depends strongly on the end anchorage of the elements [2]. Nowadays, stirrups and double-headed studs are widely used. Due to the improved anchorage, double-headed studs allow for a higher increase of the punching shear resistance [3–7], which is also reflected in approvals and code provisions (e.g. Model Code 2010 [8], ACI 318-14 [9]). The phenomenon of punching with and without shear reinforcement has been addressed extensively in literature (e.g. [10–19]).

Provided flexural and bond failure is avoided, shear-reinforced flat plates can fail in punching shear inside the shear-reinforced zone, outside the shear-reinforced zone, or close to the column due to concrete crushing. If the cross-sectional area of the punching shear reinforcement is not sufficient to prevent shear reinforcement from yielding, the failure will take place inside the shear-reinforced zone. A punching shear failure outside the shear-reinforced zone occurs if enough punching shear reinforcement is provided, but does not extend sufficiently into the slab away from the column. In the case that a failure inside and outside the shear-reinforced zone is prevented, the shear force is limited by the maximum punching shear capacity [20,21]. As reflected in design codes, the main parameters on the punching shear capacity are slab and column dimensions; concrete strength; flexural reinforcement ratio; and type and amount of shear reinforcement.

The punching shear capacity of flat plates can also be increased by using Ultra High Performance Concrete (UHPC) instead of normal strength concrete (NSC). In this paper, concrete up to a cylinder compressive strength of 50 MPa is designated as NSC. UHPC

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has a much larger concrete compressive strength greater than 150 MPa. Compared to NSC, UHPC is a much more homogenous and dense material with superior mechanical properties. Due to its pronounced brittleness, usually, the incorporation of fibres is required [22]. Recently, first attempts to replace only the critical punching shear zone with UHPC have been made [23,24].

In the present study, the combination and interaction of UHPC and double-headed studs is investigated. The aim of the test campaign is to examine whether the maximum punching shear resistance of a shear-reinforced flat plate can be increased by a built-in UHPC unit. A series of ten punching shear tests on interior slab-column connections were performed. All test specimens were provided with double-headed studs as shear reinforcement. In nine slabs, an additional element, consisting of fibre-reinforced Ultra High Performance Concrete (UHPC), was included. The UHPC unit strengthened the highly stressed compression zone at the column face.

2. Experimental program

Ten punching tests DUHPC1 to DUHPC10 were conducted on reinforced concrete slabs with double-headed studs as shear reinforcement. The tests DUHPC1 to 9 were performed at Carinthia University of Applied Sciences, Austria [25] and test DUHPC10 at RWTH Aachen University, Germany. In reference test specimen DUHPC1, no pre-fabricated built-in unit, consisting of UHPC, was provided. DUHPC1 was designed to fail at maximum load level. All further nine test slabs included a UHPC built-in unit.

In eight of these tests, the thickness of the slab and the UHPC unit was kept constant and two different outer diameters of the UHPC unit were investigated. To allow for flexibility with respect to different geometrical and structural conditions, seven elements were segmented by joints into four even-sized parts and provided with channels for subsequent insertion of the double-headed studs. To study the influence of the grout strength, two different cementitious grouts were used to fill the joints and channels. One test specimen was provided with an increased slab thickness and as a consequence with an increased UHPC unit.

2.1. Test specimens

The test slabs had a side dimension of 2.75 m in both directions (DUHPC1 to DUHPC9 with cropped corners) with a thickness of 210 mm and 310 mm for DUHPC10, respectively. Fig. 1 exemplarily shows the layout of flexural reinforcement and double-headed studs for test specimen DUHPC2. The circular column stub was cast monolithically at the centre of the slab. The column diameter was 300 mm for specimens DUHPC1 to DUHPC9 and 470 mm for DUHPC10. The distance from the extreme concrete compression fibre to centroid of tension reinforcement (effective depth) was d = 165 mm for specimens DUHPC1 to DUHPC9 and d = 260 mm for DUHPC10. The slabs were simply supported on 12 roller bearings or twelve steel rods (DUHPC10), arranged along a peripheral circle of 2.40 m diameter around the column centre. This type of specimen can represent the region of negative bending moment around an interior column [18]. The circular arranged supports simulate the line of contraflexure. Based on the assumption that in a flat plate system the radial moment is zero at a distance of approximately 0.22L from the column centre (with L being the span of the slab system), the test specimens correspond to a flat plate system with a span to depth ratio l/d of 33 (DUHPC1 to DUHPC9) and 21 (DUHPC10).

The flexural reinforcement ratio was approximately 1.90% in all tests. For the test slabs DUHPC1 and DUHPC2, ordinary reinforcing steel with a diameter of 20 mm was used. All other test specimens were reinforced with higher grade pre-stressing steel to avoid yielding of the flexural reinforcement. The diameter was 20 mm in tests DUHPC3 to DUHPC9 and 26.5 mm in test DUHPC10.

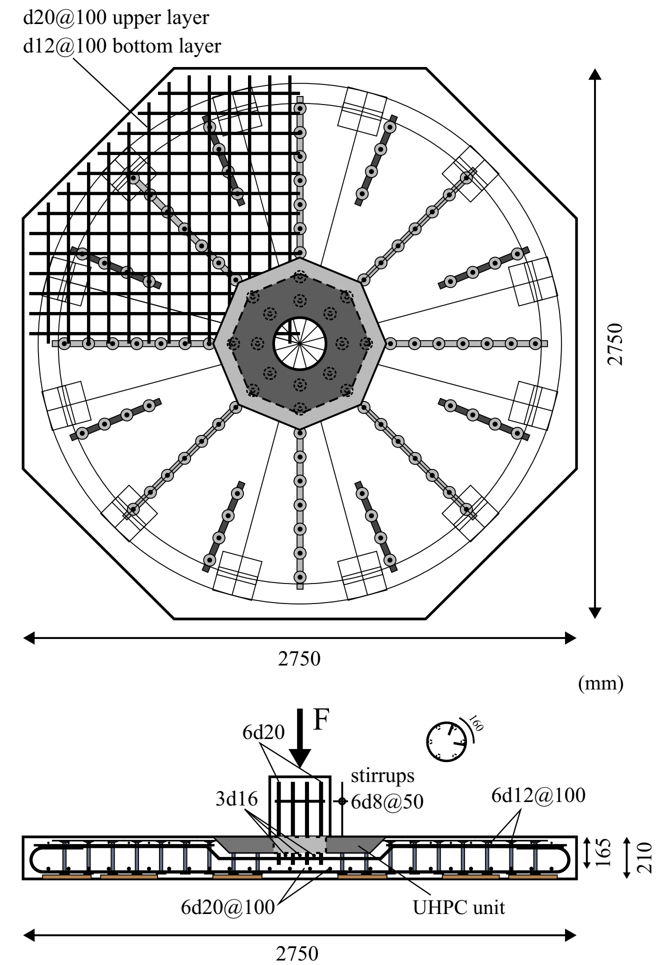

Fig. 1. Layout of flexural reinforcement and double-headed studs for test specimen DUHPC2.

A star-like layout of the double-headed studs with 8 rows was chosen for all tests. The diameter of the studs was 16 mm in tests DUHPC1 to DUHPC9 and 20 mm in DUHPC10.

The UHPC-units of test specimens DUHPC2 to DUHPC6 (Fig. 2) had an outer diameter of 715 mm, corresponding to 1.3d, with a thickness of 80 mm. For test specimens DUHPC7 to DUHPC9, the outer diameter of the UHPC unit was increased to 936 mm, corresponding to 1.9d. The outer diameter of the UHPC unit used for DUHPC10 was also equivalent to 1.9d, resulting in 1485 mm, and the thickness was increased to 100 mm.

The UHPC unit of DUHPC2 was cast monolithically including the double-headed studs and without any joints (Fig. 2a). In DUHPC3 and DUHPC10, the UHPC unit was separated into four parts with joints in between (e.g. Fig. 2b). In addition to the joints, channels were foreseen in the UHPC units of DUHPC4 to DUHPC9, in which the double-headed studs were subsequently inserted as is exemplarily shown in Fig. 2c for DUHPC4. The outline of the channels for the double-headed studs was enclosed by a perforated metal sheet, which was used as a lost formwork. The specimens DUHPC5 and DUHPC6 were similar to test slab DUHPC4, with the only difference that the channels for the double-headed studs were not enclosed by a perforated metal sheet. In test specimen DUHPC9, additional threaded rods were arranged perpendicular to the channels to reduce the cracking along the channels (Fig. 2d).