SLAB-COLUMN CONNECTION WITH EFFECTIVE LATTICE SHEAR REINFORCEMENT

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ABSTRACT

Reinforced concrete flat slabs supported by columns may fail by punching shear in form of a cone-shaped concrete breakout. To avoid this failure and to increase the shear resistance of a flat slab, shear reinforcement in the slab adjacent to the support can be used. A special punching shear lattice reinforcement with stiff anchorage and optimised inclination of the load bearing bars is able to increase the shear resistance of a slab to more than double compared with a slab without any shear reinforcement. This Filigran®-Punching Shear Reinforcement system is especially used in semi-precast flat slabs made of precast elements about 50 mm thin with in situ concrete cover. In this application gaps between the precast part and the column edge might be present. Previous experimental investigation showed no influence from a variation of the gap width on the shear resistance when this lattice shear reinforcement is placed close to the column. In addition to this detail, the upper surface of a precast column might end on a level above the lower surface of the slab. Such initial penetration of the column into the slab might reduce the height of the punching failure cone and thus the punching shear resistance of a slab. A full scale punching shear test on a 260 mm thick slab was carried out with a column penetrating 20 mm. The comparison with a test without column penetration showed no reduction of the punching shear strength. An additional comparison of these two tests with two other tests with semi-precast slabs reinforced with double headed studs confirmed the robustness of the column-slab connection reinforced with this Filigran®-Punching Shear Reinforcement which has to be placed close to the column.

1 Semi-Precast Flat Slabs

Semi-precast slabs are made of thin precast plates (fig. 1) with a thickness of about 50 mm and an in situ concrete layer on top. The prefabricated plate is reinforced with lattice girders, which ensure sufficient stiffness during transportation and erection on site. In the final stage the lower chord of the lattice girder functions as part of the bending reinforcement and the struts of the lattice girder bear as shear reinforcement.

In the early years semi-precast slabs were mainly used in one-way spanning slabs. Meanwhile semi-precast slabs are also provided as two-way spanning slabs. In this case the longitudinal reinforcement of one direction is put into the precast plates and the bending reinforcement perpendicular to this direction is laid down on the precast elements on site.

Figure 1: Precast slabs with lattice girders used for composite flat slabs

The application of flat slabs is limited due to its punching shear capacity. The punching shear resistance of a semi-precast slab could be influenced by the interface between the precast and the in-situ concrete layer. Moreover, the joints between several precast elements as well as between the elements and the column raise the question of impact on the load bearing behaviour. Therefore, punching shear tests to determine the maximum shear resistance of shear reinforcement should take into account these effects.

First full scale tests[1] with lattice girders as punching shear reinforcement in composite slabs were carried out with a type of lattice girder, which has been used as shear reinforcement in one-way span slabs for many years. These lattice girders were arranged parallel to each other with the ascending lattice struts towards the column. The upper flexural reinforcement was placed on top of the upper chord. According to these tests, an increase of the punching shear resistance, depending on the concrete class, of 20% to 30% was approved in Germany.

Eligehausen et al.[2] tested special lattice girders with stiff anchorage of the loadbearing bars and with loops protruding over the upper chord. These loops protruded into the layer of the upper flexural reinforcement. The punching shear resistance of composite slabs was increased by these girders by a factor of between 1.79 and 1.83[3]. The approved increase factor based on the German design standard was 1.7.

2 The Filigran®-Punching Shear Reinforcement

2.1 Full Scale Punching Shear Tests

Furche et al.[4] introduced a highly effective lattice punching shear reinforcement. This Filigran®-Punching Shear Reinforcement FDB II system (fig. 2) has two longitudinal lower chords and one upper chord with a diameter of 10 mm. The strut diameter is 9 mm. The characteristic yield strength of the steel is 500 MPa. The characteristic (5%-quantile) ratio of the tensile strength over yield strength is 1.05 and the elongation at maximum strength is 2.5%. All bars are ribbed.

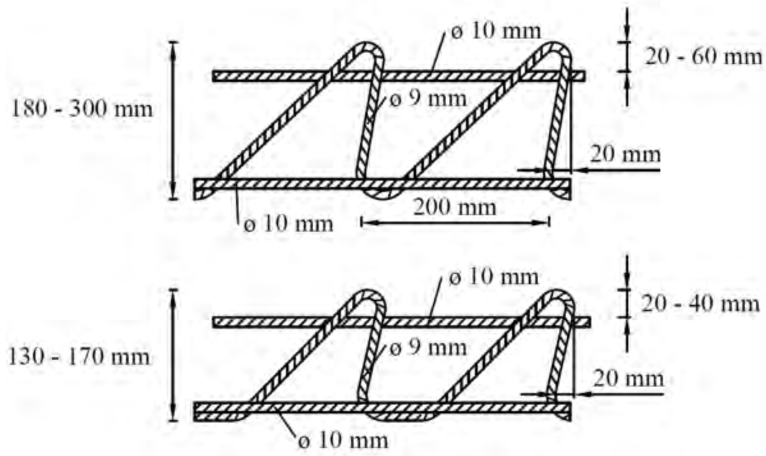


Figure 2: Filigran®-Punching Shear Reinforcement FDB II[4, 5]

Five full scale tests[4] on inner column slab connections were carried out to determine the maximum shear resistance. The slab thickness varied between $h = 180$ mm and 360 mm and the associated effective depths between $d = 145$ mm and 295 mm. Columns with square cross-sections ranged from $c = 240$ mm to 300 mm. This resulted in column perimeter to effective depth ratios of $u_0/d = 4.0$ to 8.0. The ratios of the upper bending reinforcement were chosen between $\rho_l = 0.70\%$ and 1.47%. The shear reinforcement elements were placed parallel to each other. In these tests a sufficient amount of shear reinforcement was chosen to avoid steel failure. Only in this case it is possible to determine the maximum strength of the compressive concrete strut, which characterises the maximum shear resistance according to several design models.

The test specimens were produced as composite slabs in two horizontal layers, with butt joints between the precast slabs and different distances between the precast elements to the column. The distance between the precast plates to the prefabricated column varied between 20 mm and zero. In one case the precast plates were placed 10 mm onto the column. Figure 3 shows the arrangement of the precast parts before concreting the top concrete layer. The edge of the precast slab was situated directly adjacent to the column. This arrangement was assumed to be crucial with respect to the load bearing capacity.

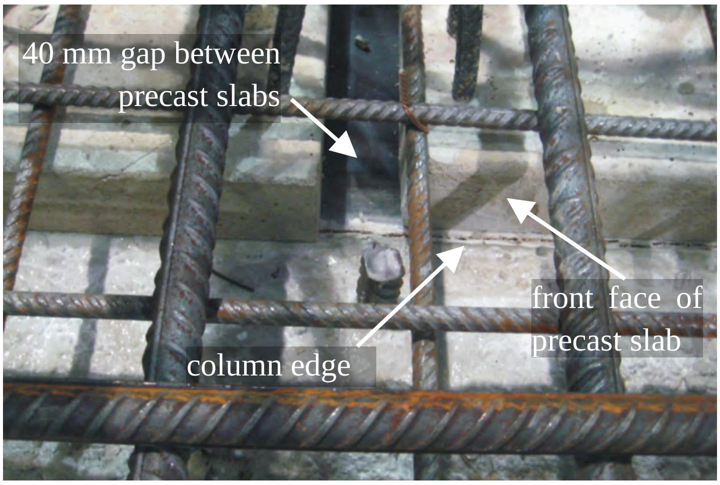


Figure 3: Arrangement of column and precast slab in tests[4]

As a result of the tests the permissible arrangement of the Filigran®-Punching Shear Reinforcement and the precast parts of the slab is specified in a European Technical Approval[5] according to figure 4. The required arrangement of the reinforcement close to the column edge in conjunction with the slight 20 mm inclination of the strut nearest to the column ensures that even steep punching shear cracks are penetrated by this strut.

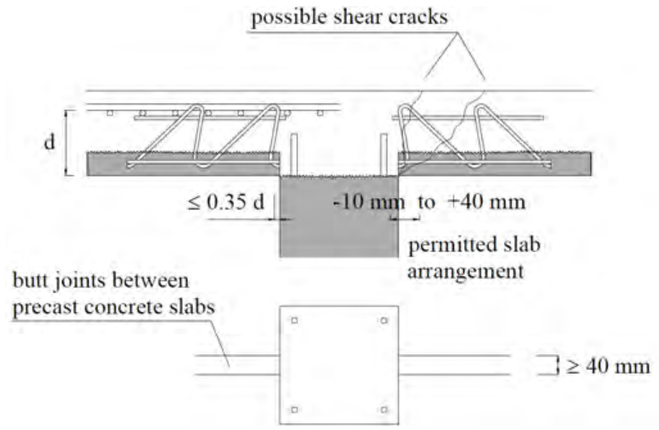


Figure 4: Permissible arrangement of the Filigran®-Punching Shear Reinforcement and precast slabs adjacent to the column[5]

2.2 Maximum Shear Resistance According to Eurocode 2

According to the design concept of Eurocode 2, the maximum punching shear strength is given as a multiple of the shear resistance of a reinforced concrete slab without punching shear reinforcement. According to the German adaptation of this standard[6], a control perimeter around the column at a distance of 2*d* is used to prove the shear resistance (fig. 5a). This design concept is applied in the European Technical Approval ETA-13/0521[5] for the Filigran®-Punching Shear Reinforcement FDB II as well as for double headed studs[7]. For this control perimeter the design resistance of concrete slabs without shear reinforcement is given by equation (1). The shear resistance depends on a factor k for size effect, the ratio ρ_l of flexural reinforcement and the characteristic compressive concrete strength f_{ck}. This equation applies for inner columns, slabs without normal stress and column perimeters greater than 4*d* and less than 12*d*. Equation (1) is here simplified without showing the minimum punching shear strength. Therefore, and for other boundary conditions, please refer to the mentioned standard[6] or the ETA-13/0521[5] respectively.

$$v_{Rd,C} = C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{1/3} \quad (1)$$

$v_{Rd,C}$ = design punching shear resistance (MPa)
$C_{Rd,c} = 0.18 / \gamma_c$ (partial safety factor for concrete $\gamma_c = 1.5$)
f_{ck} = characteristic concrete strength
$k = 1 + \sqrt{(200/d)} \leq 2$
d = effective depth (mm)
ρ_l = ratio of longitudinal reinforcement
$\rho_l = \sqrt{(\rho_{lz} \cdot \rho_{ly})}$ ≤ 0.02
$\leq 0.5\, f_{cd}/f_{yd}$

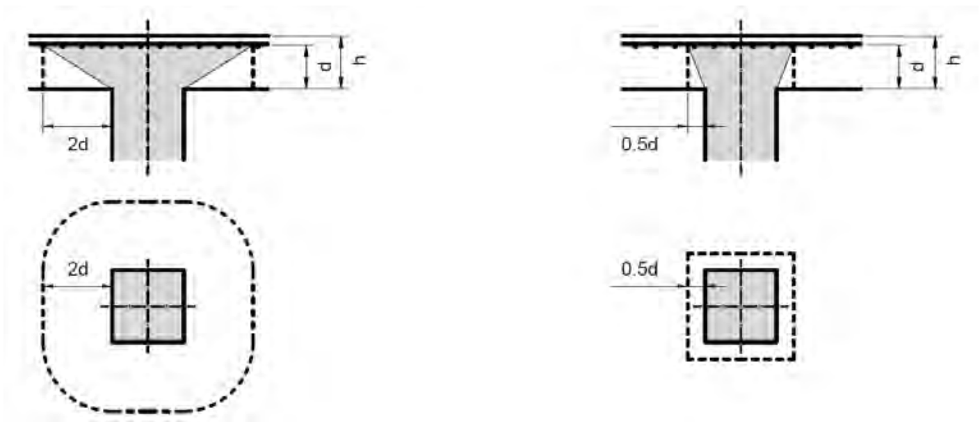
$$v_{Rd,max} = \alpha_{max} \cdot v_{Rd,C} \quad (2)$$

The maximum punching shear resistance for slabs with punching shear reinforcement is given by equation (2). The increase factor α_{max} in this equation depends on the type of shear reinforcement. Full scale tests[4] with the Filigran® -Punching Shear Reinforcement gave ratios of the tested resistance to the expected resistance according to equation (1), taking into account a characteristic concrete strength of $f_{ck} = f_{cm} - 4$ MPa with f_{cm} taken as the average strength of the tested cylinders. The individual values were between $\alpha_{max,i} = 2.16$ and $\alpha_{max,i} = 2.42$. A characteristic value of $\alpha_{max} = 2.09$ was evaluated as the 5%-quantile with a probability of 75%. Thus equation (3) is approved in ETA-13/0521[5].

$$v_{Rd,max} = 2.09 \cdot v_{Rd,C} \quad (3)$$

2.3 Maximum Shear Resistance According to ACI 318-14

According to the design concept of ACI[8], the punching shear strength must be proved in a critical section at a distance of 0.5*d* from the column. An inner column with square cross section without openings or free edges nearby leads to a critical section as shown in figure 5b. For critical sections for other boundary conditions, please refer to ACI 318[8]. The stress corresponding to two-way shear strength v_c provided by normal concrete is given by equation (4). In contrast to equation (1), there is no flexural reinforcement ratio or size effect taken into account.



a) according to DIN EN 1992-1-1/NA[6] b) according to ACI 318-14[8]

Figure 5: Control perimeter for proving the punching shear resistance

$$v_c = 1/3 \sqrt{f_c`} \quad (4)$$

v_c = stress (MPa) corresponding to two-way shear strength provided by concrete
$f_c`$ = specified compressive strength of concrete

Furche et al.[4] evaluated the full scale tests with Filigran®-Punching Shear Reinforcement FDB II and compared it to the expected figures according to equation (4). The specified compressive strength of concrete $f_c`$ as the average value f_{cm} of the tested cylinders was taken into account. The individual ratios of tested resistance to expected resistance achieved between $v_{test}/v_c = 2.15$ and 2.55 with a characteristic value of $v_{test}/v_c = 2.12$. Therefore, the maximum two-way shear resistance v_u of slabs with Filigran®-Punching Shear Reinforcement can be taken as that of double headed studs according to equation (5) which gives double the shear capacity of slabs without shear reinforcement.

$$v_u = 2/3 \sqrt{f_c`} \quad (5)$$

It was shown in tests that the shear resistance increases with the flexural reinforcement ratio. An evaluation of tests with a ratio of greater than 1% only gives a higher characteristic increase factor of 2.27. If flexural reinforcement of this amount is provided, a higher maximum two-way shear resistance of $v_u = 0.75 \sqrt{f_c`}$ can be endorsed[4].

3 Column Precast too High

3.1 The Problem

Columns are typically concreted prior to pouring the slab. Depending on the execution quality, the upper surface of the precast column may be situated on the level of the lower surface of the slab or deviating from it. Independent of the execution method (monolithic or composite slab), a column cast too high penetrates into the subsequently poured slab. According to some design recommendations, the effective height *d* of the slab should be reduced to d_v (fig. 6) in such cases. According to this approach, the critical shear crack ends at the upper edge of the column. This assumption is based on cases of failures of monolithic concrete slabs without shear reinforcement where an initial penetration of the column was found subsequently. The author has no knowledge of any experimental investigations to study this effect on the punching shear capacity of the slab. It might well be the case that the assumption according figure 6 is conservative, especially in cases of slabs with punching shear reinforcement. On the other hand, it could happen that in composite slabs a column concreted too high leads to a small gap between the precast slab and the column. Such a gap could also have a negative effect on the punching shear capacity.

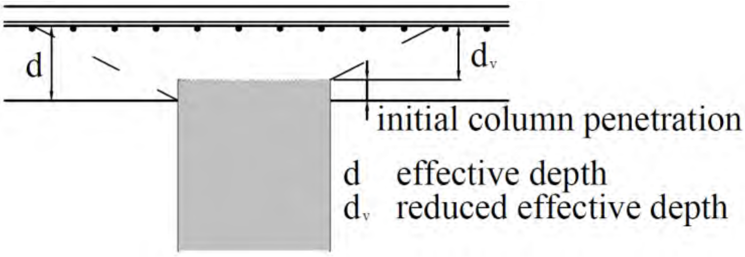
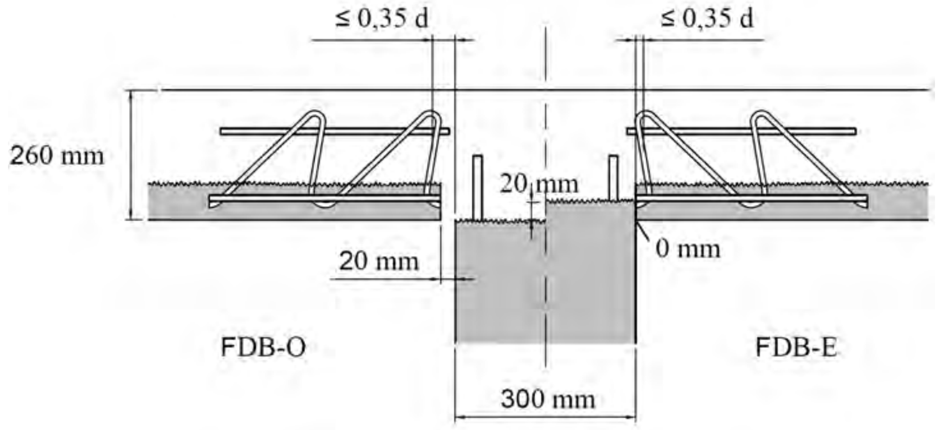


Figure 6: Assumption of reduced effective depth in case of too high concreted column to be proven

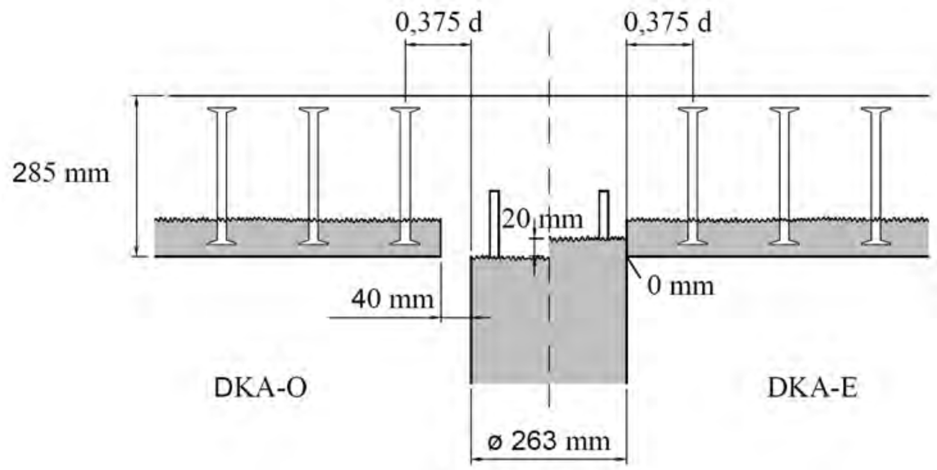
3.2 Punching Shear Tests

In punching shear tests[4] with composite slabs it was already shown that placement of precast slabs directly near the column has no negative effect on the loadbearing capacity. An additional test was carried out to investigate the behaviour in case of columns concreted too high. In addition to this, the question was raised whether composite slabs reinforced with double headed studs show a similar behaviour.

Furche[4] described a test with the Filigran®-Punching Shear Reinforcement in a composite slab with an overall thickness auf 260 mm. The distance between the precast part and the column was 20 mm and the upper surface of the column was situated on the level of the lower surface of the slab (fig. 7a, left side). This test was taken as a reference test. In a new test, the upper column surface was situated 20 mm above the lower surface of the slab and the precast part was placed flush with the column (fig. 7a, right side). The Filigran®-Punching Shear Reinforcement in both arrangements was situated close to the edge of the precast slab part. This ensured the maximum distance of the loadbearing bar to the column side face of 0.35*d*.



a) with Filigran®-Punching Shear Reinforcement FDB II (FDB)



b) with double headed studs (DKA)

Figure 7: Arrangement of precast slabs and punching shear reinforcement in reference tests (notation O) und additional tests (notation E)

Kueres et al.[9] described two further tests with double headed studs function as punching shear reinforcement. In a reference test with a 285 mm thick composite slab, the precast slab part had a distance to the column of 40 mm (fig. 7b, left side). In a new test, the upper column surface was situated 20 mm above the lower surface of the slab and the precast part was placed flush with the column (fig. 7b, right side). The studs close to the edge in both arrangements had a distance to the column of 0.375*d*. This was within the permissible range[7] of 0.35*d* and 0.5*d*.

All four punching shear tests were carried out at the same test facility. Figure 8 shows one half of each new test specimen and the test arrangement. In all four tests a 40 mm wide gap between the precast slab parts was poured together with the top layer of the composite slab. In both tests with Filigran®-Punching Shear Reinforcement FDB II the columns had square cross sections. Both specimens with double headed studs had columns with circular cross sections.

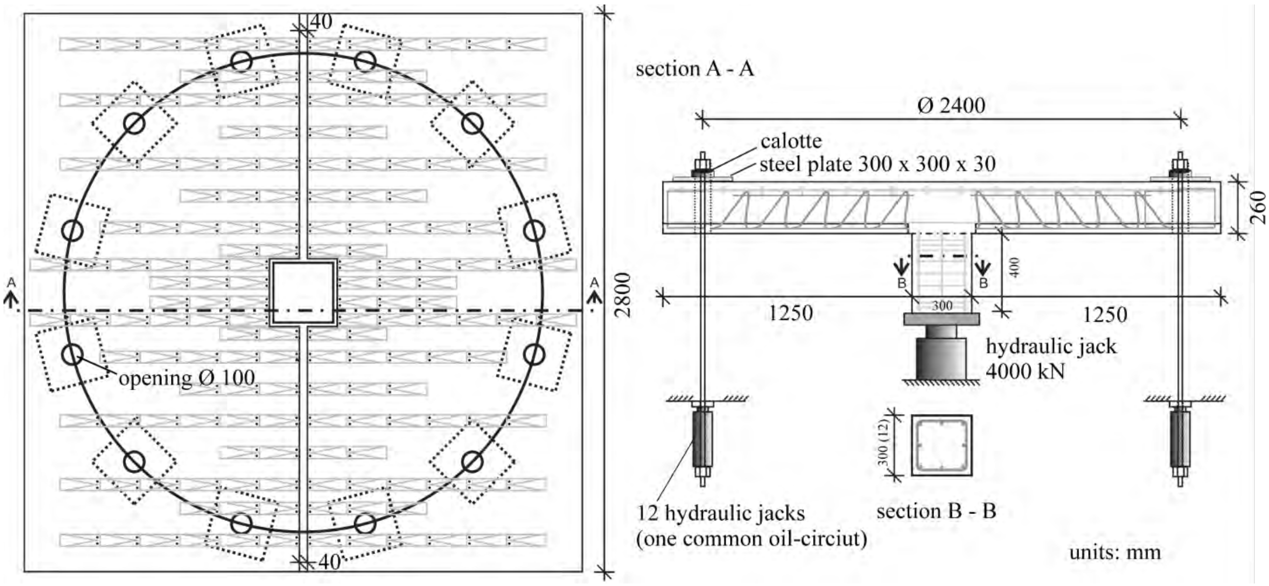


Figure 8: Test specimens and test arrangement of the additional test[9]

Figure 9 shows the test specimen FDB-E from below. At some locations it was possible to slide in a plastic card and an annular clearance became obvious.

Figure 9: Test specimen FDB-E from below with a gap between column and precast slab

At the beginning of each test, the load was increased up to the service load, which was taken as the expected failure load divided by 2.1. The load was then cycled 10 times between this level and 50% of this level. Afterwards the load was increased incrementally to the maximum load. Figure 10 shows the load-deflection curve of the tests. The initial load V was related to the expected characteristic load $V_{Rk,c}$ according to equation (1) to allow for easy comparison of the tests. The deflection was taken as the average of the deflections measured at four points at the circle of loading (fig. 8).

In both tests with the Filigran®-Punching Shear Reinforcement it was possibly, following a reduction of the load, to increase the load again to about 80% of the maximum load. This demonstrates the ductile behaviour of the column slab connection. Both load deflection curves are quite similar (fig. 10, right side). No effect of the penetration of the column could be seen.

The load-deflection-curves of the tests with double headed studs (fig. 10, left side) deviate above load levels of 1.5 times of the resistance of a slab without shear reinforcement. A reloading of the test specimen DKA-E after reaching the maximum load was not done due to excessive deflection of the specimen.

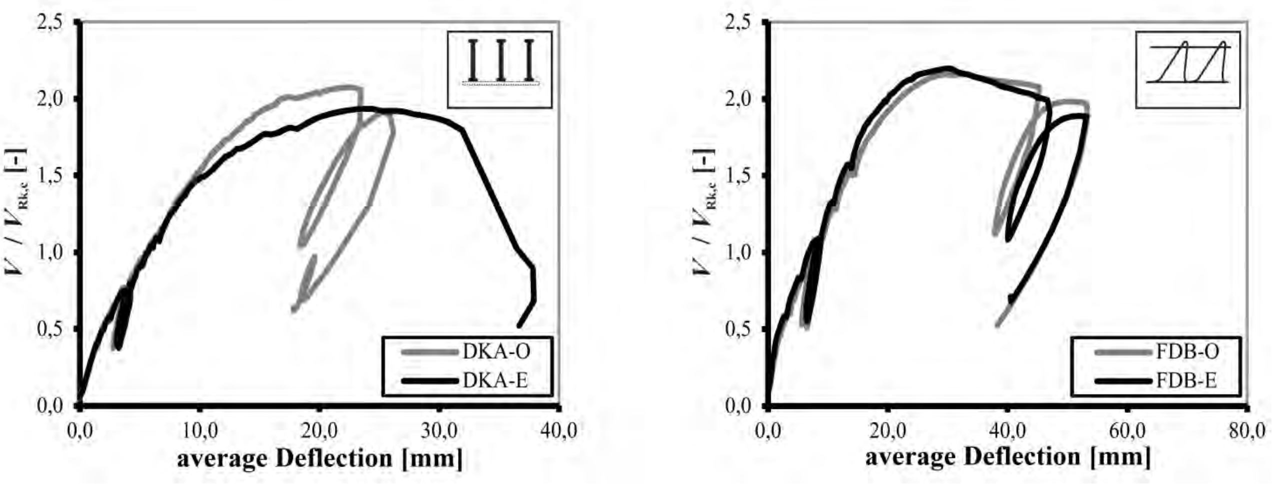


Figure 10: Load-deflection-curve of the punching shear tests[9] compared

After the tests the specimens were cut in the plane of the side surface of the column to study the internal crack pattern (fig. 11). Test specimens with double headed studs show inclined shear cracks typical for this type of reinforcement. A steep shear crack close to the column can be observed in test DKA-E as an initial failure crack. The crack tip points to the upper edge of the column concreted 20 mm too high. In the reference test DKA-O without column penetration the crack tip sits lower.

The crack pattern of tests FDB-O and FDB-E with Filigran®-Punching Shear Reinforcement FDB II show similar characteristic. In the sectional plane parallel to the longitudinal direction of the shear reinforcement only some cracks, which combine in the layer of the upper bending reinforcement can be observed. The sectional plane perpendicular to the above-mentioned one shows fine distributed cracks. A steep crack close to the column, which is not penetrated by shear reinforcement is not observed. This is determined by the reinforcing system, which was placed close to the column at a distance smaller than 0.35*d* (fig. 7a).

In every test specimen a horizontal crack in the compressive zone approximately in the middle of the precast part of the slab can be observed. Such cracks in the compression zone are also observed in other punching shear tests with high shear capacity.

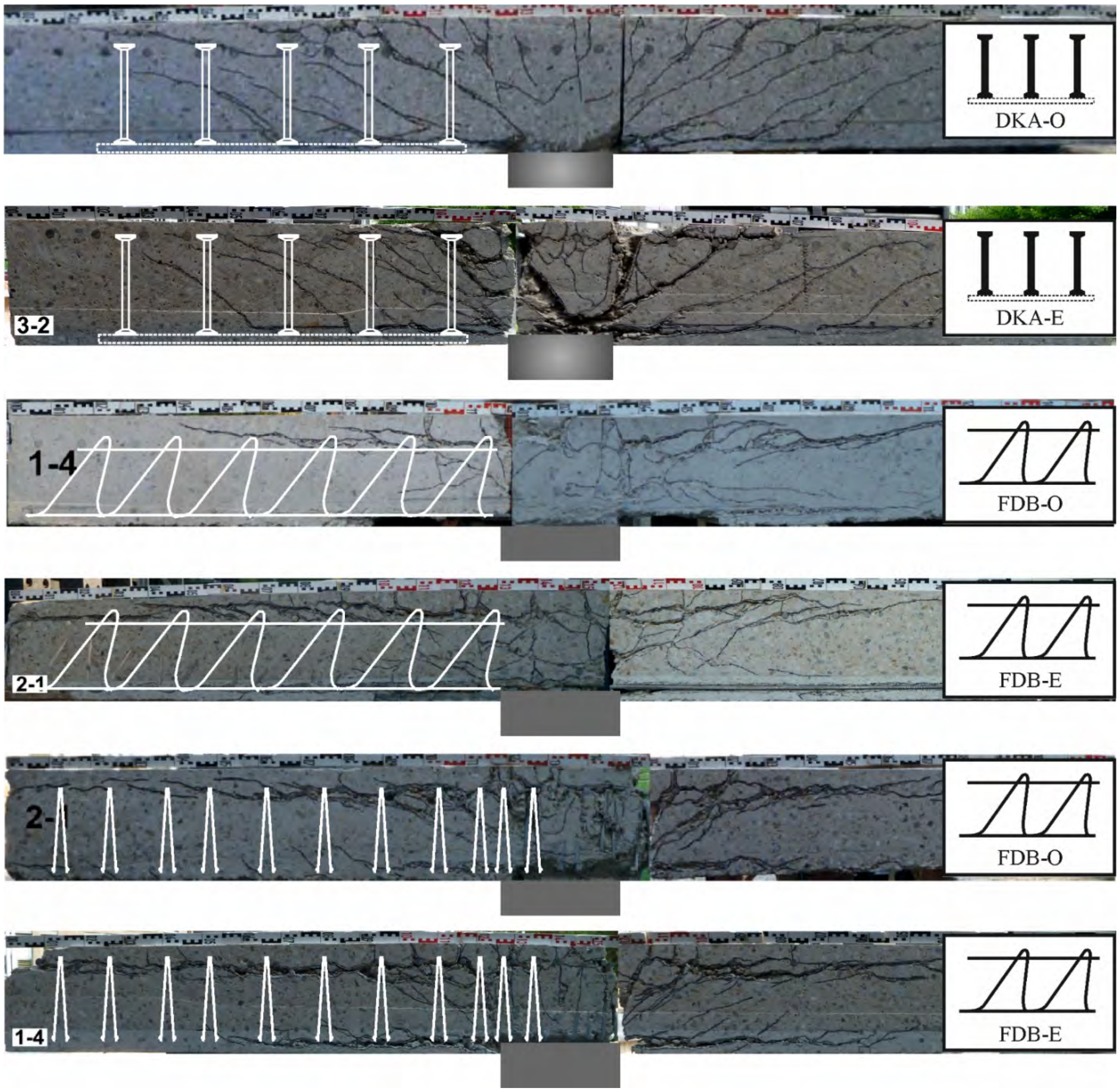


Figure 11: Crack Patterns in saw cuts of the test specimens[9]

Table 1 lists key parameters and results of the described tests. The achieved punching shear resistance is compared to the expected resistance of a slab with the same geometry and concrete strength but without shear reinforcement.

3.3 Results and Evaluation

Test FDB-E with the Filigran®-Punching Shear Reinforcement FDB II and an initial column penetration of 20 mm achieved an increase factor of $\alpha_{max,i}$ = 2.20 compared to the resistance of a slab without shear reinforcement. This value is about 2% higher than the compared value $\alpha_{max,i}$ = 2.16 in the test without column penetration. According to the assumption shown in figure 6, column penetration reduces the effective depth as well as the design perimeter. With the geometry of the tested specimen a reduction of the punching shear resistance of about 15% had been expected, which translates to an expected increase factor $\alpha_{max,i}$ = 1.84 in relation to the reference test.

Therefore, the test with the Filigran®-Punching Shear Reinforcement did not confirm the model according figure 6. The punching shear resistance was not reduced by the initial column penetration and was covered well by equation (3).

Table 1: Parameter and results of the punching shear tests

	Double headed studs		Filigran®-Punching Shear Reinforcement FDB II	
Test notation	DKA-O	DKA-E	FDB-O	FDB-E
Reference	[9]	[9]	[4, 9]	[9]
Distance between precast slab and column	40 mm	0 mm	20 mm	0 mm
Penetration of column	0 mm	20 mm	0 mm	20 mm
Effective depth d	250 mm	250 mm	209 mm	215 mm
Column cross section	∅ 263 mm		300 mm x 300 mm	
Concrete cylinder strength top layer $f^{t}_{cm,cyl}$	29.9 MPa	31.2 MPa	21.9 MPa	21.6 MPa
Concrete cylinder strength precast part $f^{p}_{cm,cyl}$	40.7 MPa	42.3 MPa	22.7 MPa	22.9 MPa
Longitudinal reinforcement ratio ρ_l	1.25%	1.25%	0.70%	0.69%
Expected resistance of a slab without shear reinforcement $V_{Rk,c}$ [a)]	1003 kN	1020 kN	661 kN	682 kN
Maximum load V_u [b)]	2085 kN	1975 kN	1428 kN	1500 kN
Resistance increase factor in test $\alpha_{max,i} = V_u / V_{Rk,c}$	2.08	1.94	2.16	2.20
Approved increase factor α_{max}	1.96 [7]		2.09 [5]	

a) according to equation (1) taking into account $f_{ck} = f^{t}_{cm,cyl} - 4$ MPa
b) Press load and dead load

The estimated increase factor is shown in figure 12 together with other test results[4]. In these tests[4] the distance of the precast part to the column edge was varied and the lower surface of the precast columns was situated on the level of the lower slab surface. All achieved results were - while scattered - in the range above the approved[5] increase factor of $\alpha_{max} = 2.09$, which was determined in tests with Filigran®-Punching Shear Reinforcement in composite slabs.

Test DKA-E with double headed studs and an initial column penetration of 20 mm achieved an increase factor relative to the expected resistance of a slab without shear reinforcement of $\alpha_{max,i} = 1.94$. This figure is about 7% lower than $\alpha_{max,i} = 2.08$, which was estimated in the reference test without column penetration. According to the assumption shown in figure 6, a reduction of the punching shear resistance of 14% or a factor of $\alpha_{max,i} = 1.79$ respectively had been assumed. The achieved resistance in the test was therefore in between the comparative test result without column penetration and the assumed resistance taking into account a reduced effective depth.

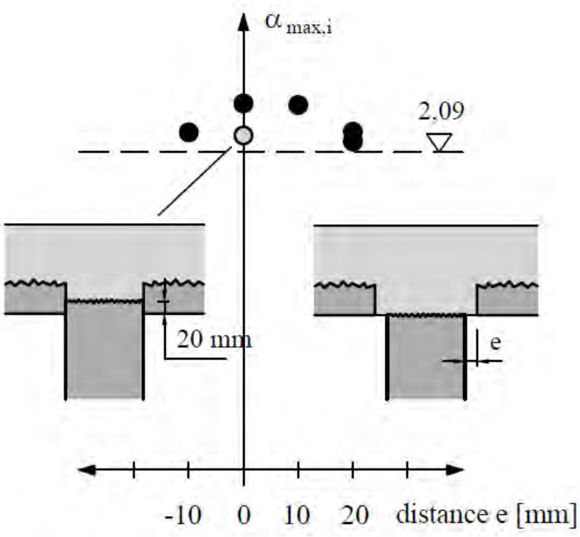


Figure 12: Increase factors $\alpha_{max,i}$ of the Filigran®-Punching Shear Reinforcement FDB II in tests with composite slabs with[9] and without[4] column penetration into the slab

3.4 Recommendations

In the test with the Filigran®-Punching Shear Reinforcement FDB II and an initial column penetration of 20 mm a shear resistance higher than the expected and approved[4] at a value of α_{max} = 2.09 was reached. This reinforcement system appears robust against small deviations from the planned height. This finding is supported by the fact that the approved increase factor was evaluated in tests with composite slabs with pre-existing vertical bond interfaces close to the column (figure 3). Therefore, it can be endorsed neglecting minor initial column penetrations in calculations when using this reinforcement according the approved application[5].

On the other hand, the single test with double headed studs showed a reducing effect from an initial column penetration on the shear resistance. This suggests that it is prudent to take an initial column penetration into account by reducing the effective depth when calculating the punching shear resistance of the slab.

As far as further tests offer additional information about the effect of initial column penetration into the slab Kueres et al.[9] recommended situating the upper level of a precast column below or on the level of the upper surface of the slab in any case. In case of a higher concreted column it is recommended to calculate the punching shear resistance with a reduced effective depth. This can also be done in cases of higher column penetration than tested.

4 Conclusion

The Filigran®-Punching Shear Reinforcement FDB II was developed to increase the punching shear resistance of flat slabs. The maximum shear resistance of 2.09 times the resistance of a slab without shear reinforcement was determined as a characteristic value in tests with composite slabs. In these tests joints between precast elements as well as between the precast part and the column were tested. Despite these boundary conditions it raised the question whether an initial column penetration reduces the effective height of the slab and therefore its shear resistance.

A full scale test with a column penetration of 20 mm into a 260 mm thick slab was carried out and compared to a previous test carried out with the same dimension and the same test device. The penetration showed no effect on the load bearing behaviour. An additional test with double headed studs showed a slight decrease of the resistance in case of column penetration. This test and limited other investigations lead to the recommendation to precast a column not higher than the lower surface level of the slab or to calculate the resistance with a reduced effective slab depth.

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