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Technical paper

Improving the punching shear and shear capacity of reinforced concrete elements with a new post-installed retrofitting system

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ABSTRACT

Finding appropriate strengthening solutions for existing reinforced concrete (RC) elements is always a challenge for structural engineers. Additional load capacity may be needed as the change of type of occupancy and more restrictive design standards require higher load levels or different detailing of reinforcement.

This paper introduces a post-installed retrofitting system consisting of an adhesive and a concrete screw anchor that can be used to improve either the pure shear capacity or the punching shear capacity of a RC beam or slab. This post-installed retrofitting system acts as shear reinforcement that can be installed with relatively minimal disruption as it is only installed at the soffit of the RC element being strengthened. The system was tested for its suitability and the results were approved by the German Construction Authority with a National Technical Approval. Published parameters are used for the standard methods of detailing shear and punching shear of a RC element according to EN1992-1 and EN1992-2. Calculations and tests have shown that with the use of this post-installed retrofitting system, the shear strength of existing concrete elements can increase by up to 100% and consequently increase the lifetime of a structure. This paper also discusses the test methods employed, the test results, and sample projects that made use of the said system. Another important finding is the substantial savings in project cost attributed to the installation methodology that comes with the system.

1 The post-installed retrofitting system

1.1 Description of the system

The post-installed retrofitting system employs bonded concrete screw anchors. This system consists of two essential components, a self-tapping concrete screw anchor and a two-component injectable organic adhesive, as shown in Figure 1. The concrete screw anchor transfers forces to the concrete member via a mechanical interlock between the screw anchor thread and the hole cavity. This mechanical interlock is achieved during the installation of the screw anchor, where thread tapping into the wall of a pre-drilled hole occurs. The adhesive, on the other hand, bonds the screw anchor to the hole cavity. Mechanical interlock transfers loads immediately after installation, while the bond effectively adds capacity after the adhesive becomes fully cured. "RELAST" is the proprietary name of this hybrid post-installed retrofitting system.

Although the system is composed of known post-installed anchor components, it is not considered as a post-installed anchor. Its evaluation and force-transfer mechanism is like a cast-in rebar. As such, the related design approach is therefore not covered in EN 1992-4:2018 "Design of post-installed and cast-in fastenings in concrete". However, EN 1992-1 "Design of concrete structures – Part 1-1: General

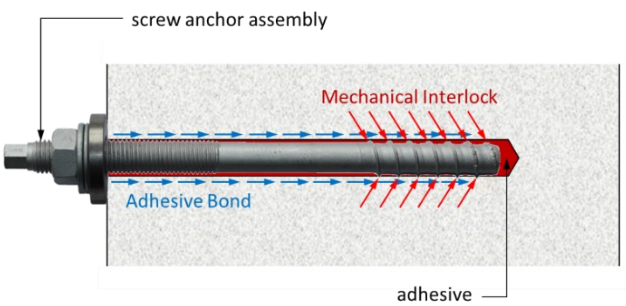

Figure 1. Würth RELAST bonded screw anchor and its load-transfer mechanism.

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rules and rules for buildings" and in EN 1992-2 "Design of concrete structures – Part 2: Concrete bridges – Design and detailing rules" provide guidance for designing shear and punching shear using RELAST.

1.2 Scientific research, test and assessment, technical product specification

The components that make up RELAST are post-installed anchors which were successfully assessed and granted construction approval many years back in Europe. The European assessment covers the following aspects:

1. characteristic resistance to tension or shear,
2. sensitivity to different installation and service temperatures,
3. freeze/thaw conditions,
4. increased concrete crack width,
5. crack cycling under load,
6. repeated loads,
7. sustained loads,
8. various environmental exposure such as high alkalinity and sulphurous atmosphere,
9. the robustness of the anchor when installed in dry and water saturated concrete with different installation directions.

The mentioned approval, enabled the anchor to be designed and used in various structural anchoring applications successfully.

Since RELAST and its 'retrofitting use' do not fully align with post-installed anchoring models, additional tests and assessments were conducted to get construction approval for retrofitting applications. During a period of approximately 7 years, a number of large scale tests helped to investigate the real behaviour of the RELAST system.

Real-life retro-fitting on several bridges and buildings in Germany and Austria demonstrated the practicability of the system.

The additional large scale tests were conducted at the University of Innsbruck and at the Universität der Bundeswehr München (Fig. 2 and 3.).

1.2.1 Laboratory tests related to the shear capacity

Four-point bending tests on reinforced concrete beams with a span of 3.5m were setup to investigate the influence of screw anchor size/type, arrangements of bonded/un-bonded installation, and anchoring depth (Fig 4.), to the shear performance of the beam.

Further 4-point tests on one-way slabs investigated the influence of the slab height.

Three pulsating load tests were conducted to evaluate the performance of retro-fitted beams under $5x10^6$ load cycles. The amplitude of the load applied, had a lower bound equal to one-third of the static ultimate load and the upper bound was two-thirds of the static ultimate load. No failure was identified.

The test setup and the results are described in detail by Lechner in [2]. The results of the test show that the retro-fitted beam achieved at least 100% shear capacity improvement compared to components without shear reinforcement.

Based on above tests, the characteristic values used for the design were derived and are detailed in the corresponding Technical Product Specifications Z-15.1-344, published in October 2019 [3].

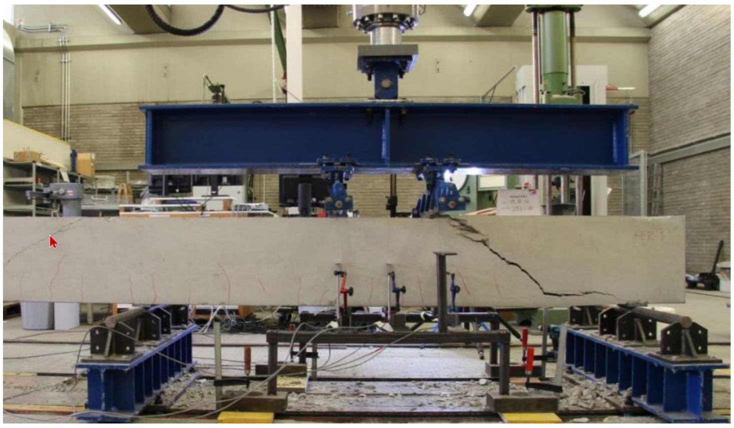

Figure 2. Large scale shear tests [1]

Figure 3. Large scale punching shear tests [1]

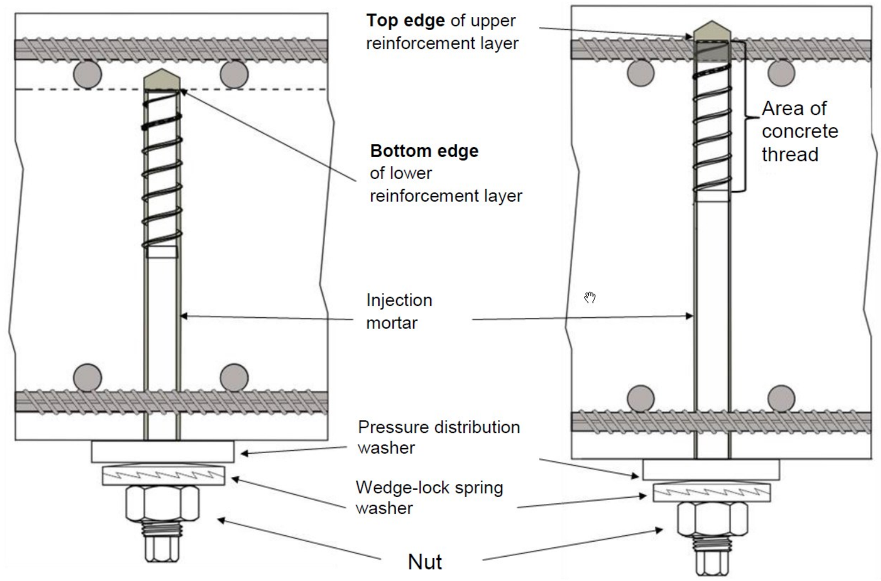

Figure 4. Optional installation conditions

1.2.2 Laboratory tests related to the punching shear capacity

The test rig of the very first punching shear tests is shown in Figure 5. In this test, 32 bonded concrete screw anchors in 8 radial rows of 4 were installed (Fig. 3).

Based on the results obtained from the tests described above, two research projects investigated the influence of screw anchor size/type, arrangements of bonded/unbonded installation, anchoring depth, and different ratios of the longitudinal reinforcement to the punching shear performance of the test specimen.

Pulsating loads on the retro-fitted slab with $2x10^6$ load cycles and a load amplitude calculated from a lower bound equal to one-third of the static ultimate load and the upper bound equal to two-thirds of the static ultimate load, did not result in visual signs of damage. Residual static punching afterwards resulted in a failure load equivalent to the static ultimate load.

The test setup and the results are described in detail by Lechner in [2]. Summarily the retro-fitted components achieved up to 40% punching shear capacity improvement compared to components without punching shear reinforcement.

Based on the above tests, the characteristic values used for the design were derived and are detailed in the corresponding Technical Product Specifications Z-15.1-345, published in October 2019 [4].

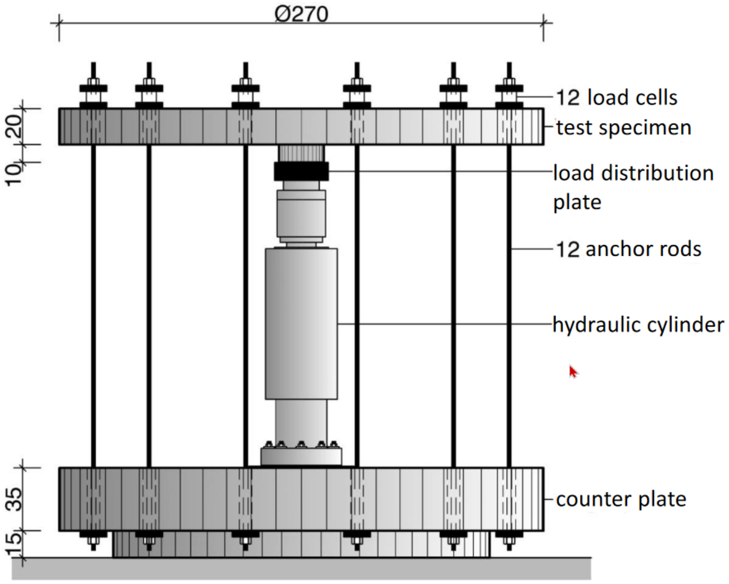

Figure 5. Test setup for the punching shear capacity tests [2]

1.3 Limitations on the use of the application

As previously mentioned, the punching shear and shear capacities are calculated using EN 1992-1 "Design of concrete structures – Part 1-1: General rules and rules for buildings" and in EN 1992-2 "Design of concrete structures – Part 2: Concrete bridges – Design and detailing rules". The European design standard and approval provide detailed guidance on the use of RELAST for retrofitting applications. Many local codes outside Europe, unfortunately, do not provide the same level of detail and guidance in the design of post-installed punching shear reinforcement. Still the said European approach may be implemented to a level that satisfies the respective country's performance requirements.

It is important to note as well that the approach detailed in this paper does not take existing punching shear or shear reinforcement into account.

The product also has minimum edge distance and spacing requirements which might not always be applicable to actual site conditions. As a consequence of a minimum embedment depth, there is a minimum concrete thickness of 200mm to observe. In the case of a punching shear retrofiting, the RELAST system is only applicable up to a maximum slab thickness of 1100mm.

The bonded concrete screw anchor can be used in corrosive environment classes C1 (minor) up to C5 (very strong) according to EN ISO 9223 and service temperature between -40°C to 80°C. The Technical Specification covers concrete strength classes for C20/25 to C50/60 and allows the design under normal load cases with static, quasi-static, and fatigue loads.

2 Case study 1 - improving the shear capacity

2.1 Design parameters to use for retrofitting a single-span concrete slab bridge

In the rehabilitation of a single span concrete slab bridge (Fig. 6), the shear capacity is to be improved by only accessing the underside of the bridge.

The following design parameters are given for the design:

Span length:	l = 15.00 m
Bridge width:	w = 9.00 m
Slab thickness:	h = 0.50 m
Effective depth of the cross-section:	d = 0.46 m
Concrete strength class:	C 50/60
Maximum acting design shear load:	$V_{Ed,max,slab}$ = 712 kN/m

By calculating design shear resistance of the member without shear reinforcement, areas (Fig. 7) requiring design shear reinforcement and consequently retrofitting for shear were identified:

Acting design shear load Area I:	$V_{Ed,max,I}$ = 500 kN/m
Acting design shear load Area II:	$V_{Ed,max,II}$ = 300 kN/m

Figure 6. Single-span concrete slab bridge

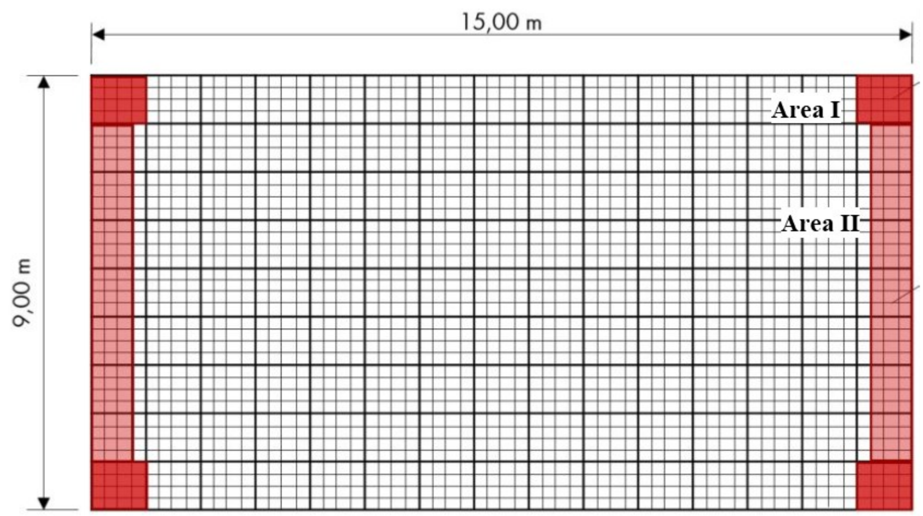

Figure 7. Various areas of the single-span concrete slab bridge

2.2 Design and detailing

The design of members with shear reinforcement is based on a truss model (Fig. 8), in which we take α = 90° and θ = 45° and as given, the inner lever arm with z = 0.9d = 0.414 m and the minimum width of the compression chord b_w = 1 m.

In this model, it is required to verify that both, the design resistance of the compression strut and of the tension tie is bigger than the acting design shear load in each area. The retrofitting bonded concrete screw anchor is taking on the task of the cast-in shear reinforcement.

2.2.1 Verification of the compression strut

The resistance of the compression strut [5] (6.9), [3]

$$V_{Rd,max} = \frac{1}{2} \cdot b_w \cdot z \cdot v_1 \cdot f_{cd} = \\ = \frac{1}{2} \cdot 1 \cdot 0.414 \cdot 0.75 \cdot 28.3 = 4394 \frac{kN}{m} \quad (1)$$

results in an utilisation level of the compression strut of

$$\frac{V_{Ed,max,slab}}{V_{Rd,max}} = 0.162. \quad (2)$$

In accordance with [3] and [5] the maximum permissible spacing from Table 1 must be taken into account

Table 1. Maximum permissible spacings [3]

Shear force ratio	max. longitudinal spacing $s_{l,max}$	max. longitudinal spacing $s_{l,max}$
$V_{Ed} \leq 0.3 \cdot V_{Rd,max}$	$0.7 \cdot h$	h
$0.3 \cdot V_{Rd,max} \leq V_{Ed} \leq 0.6 \cdot V_{Rd,max}$	$0.5 \cdot h$	h
$V_{Ed} > 0.6 \cdot V_{Rd,max}$	$0.25 \cdot h$	h

and are with the given member thickness $s_{l,max}$ = 0.35 m and $s_{t,max}$ = 0.5 m.

2.2.2 Verification of the tension tie

The resistance of the tension tie is calculated with [5] (6.8), [3]

$$V_{Rd,s} = a_{sw} \cdot z \cdot f_{ywd,ef} \quad (3)$$

where the effective design yield strength of the bonded concrete screw anchor is

$$f_{ywd,ef} = c_1 \cdot \frac{f_{ywk}}{\gamma_s} + c_2 \cdot \frac{v_1}{\rho_{sw}} \cdot f_{cd} \leq \frac{f_{ywk}}{\gamma_s} \quad (4)$$

The introduction of the effective yield strength takes into account that the concrete screw cannot be utilised to their full yield capacity. The parameters c_1 and c_2 are derived from tests and incorporate diameter and embedment depth of the concrete screws. While c_1 represents the ratio of the concrete screw's resistance of the total shear resistance, c_2 is the portion of the concrete depending resistances.

The ratio of cross section a_{sw} for improving the shear capacity is calculated with

$$a_{sw} = \frac{A_{sw,sc}}{s_l \cdot s_t} \quad (5)$$

For further verification we chose the RELAST system 22 with a diameter M20. The selected longitudinal spacing s_l = 0.30 m and transverse spacing s_t = 0.30 m are below their respective maximum allowed values.

The material parameter are given in Table 2 [3].

With the cross section of the screw anchor

$$A_{sw,sc} = \left(\frac{d_{k,1}}{2}\right)^2 \cdot \pi = 3.3cm^2 \quad (6)$$

we calculate a_{sw} = 36.67cm²/m² or the relative ratio to ρ_{sw} = 0.36%.

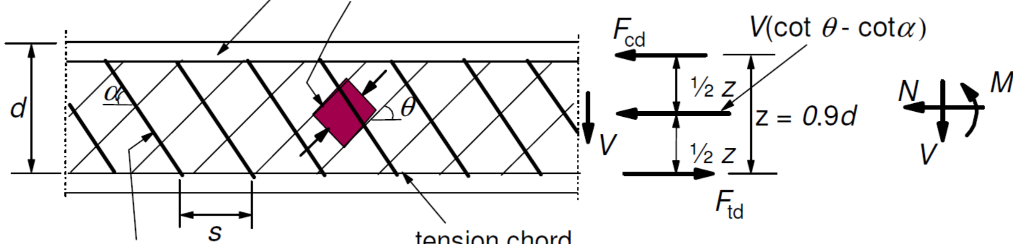

Figure 8. Truss model [5]

Table 2. Dimensions and material of the concrete screw anchor [3]

Bonded screw anchor	Connecting thread	External diameter	Core diameter	Core diameter	Yield strength
		d_G	$d_{k,1}$	$d_{k,2}$	f_{ykw}
		mm	mm	mm	N/mm²
Würth RELAST 22	M20	24.3	20.5	16.93	500

With the second load factor c_2 = 0.046 and the first load factor c_1 = 0.2384 according to table 5 in [3] for the installation condition below the upper reinforcement layer (Fig. 4 left), the effective design yield strength of the bonded concrete screw anchor is calculated to $f_{ywd,ef}$ = 369.91 N/mm² ≤ 434.78 N/mm².

The required cross section of the screws to verify successfully the tension tie in area I is

$$a_{sw.req} = \frac{V_{Ed,max,I}}{z \cdot f_{ywd,ef}} = \\ = \frac{5000 cm^2}{0.414 \cdot 369.91 m^2} = 32.65 \frac{cm^2}{m^2} \leq 36.67 \frac{cm^2}{m^2} \quad (7)$$

and to verify successfully the tension tie in area II

$$a_{sw.req} = \frac{V_{Ed,max,I}}{z \cdot f_{ywd,ef}} = \frac{3000 cm^2}{0.414 \cdot 369.91 m^2} = \\ = 19.59 \frac{cm^2}{m^2} \leq 36.67 \frac{cm^2}{m^2} \quad (8)$$

The installation plan of Figure 9 shows the screw with the respective selected longitudinal spacing s_l = 0.30 m and transverse spacing s_t = 0.30 m for area I and II, and an edge distance of c = 0.15 m where it applies.

Each bonded concrete screw anchor is installed with an embedment depth of h_{nom} = 210 mm and provides a minimum for the projected thread length of $t_{üb}$ ≥ 52 mm to accommodate the big washer, the wedge-lock spring washer and the nut.

3 Case study 2 - improving the punching shear capacity

Several documented structural collapses in different parts of the world show that insufficient resistance to punching shear is the main reason for the collapse. Punching shear failure is particularly dangerous because of its, relatively, brittle behaviour. Some examples of documented failures related to punching shear are the Sampoong Department Store (Seoul, South Korea) and The Piper's Row Carpark, (Wolverhampton, GB). A common feature between these structures is the use of flat slabs.

Punching shear capacity is primarily influenced by the concrete strength, flexural reinforcements, geometry and dimension of columns, and the size effect. Punching failure can potentially result from design/planning errors, construction mistakes, changes in the type of occupancy of the building, and changes in the building codes. The punching capacity of new concrete structures can readily be addressed by following the provisions of new codes and standards. Extra punching shear reinforcements can be built-in to the design, and pre-installed before concrete is poured. For existing concrete structures however, a post-installed approach is more desirable. There are a number of different punching shear retrofitting approaches, but this paper focuses on a proprietary post-installed retrofitting system that is designed to significantly improve punching shear capacity, in a relatively quicker time, while the structure remains operational.

3.1 Design parameters to use for retrofitting a flat concrete slab

In the rehabilitation of an office building, the punching shear capacity of the flat concrete slab is to be verified and improved when necessary. A representative area of the slab is shown in Figure 10.

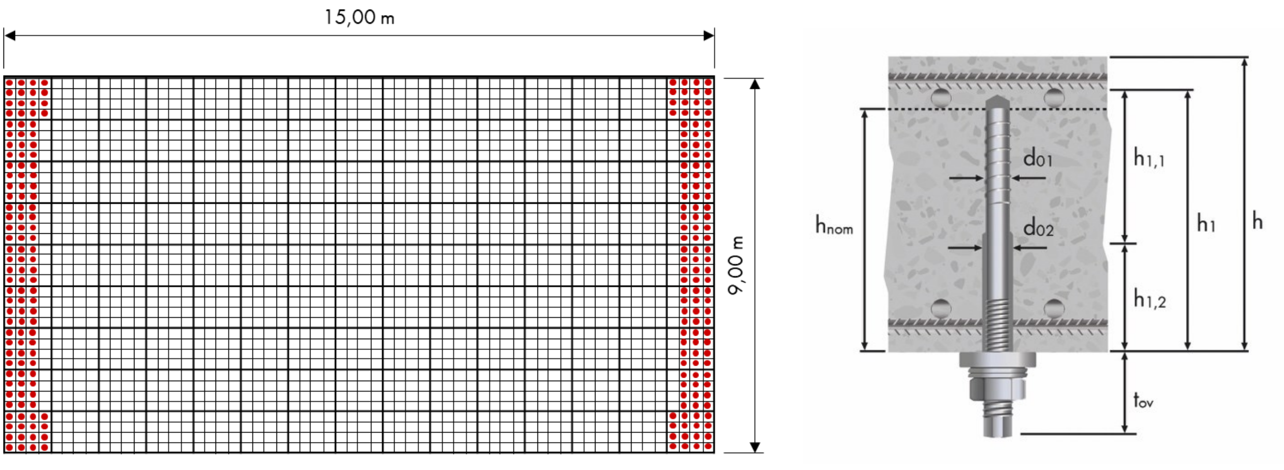

Figure 9. Installation plan and installed bonded concrete screw anchor

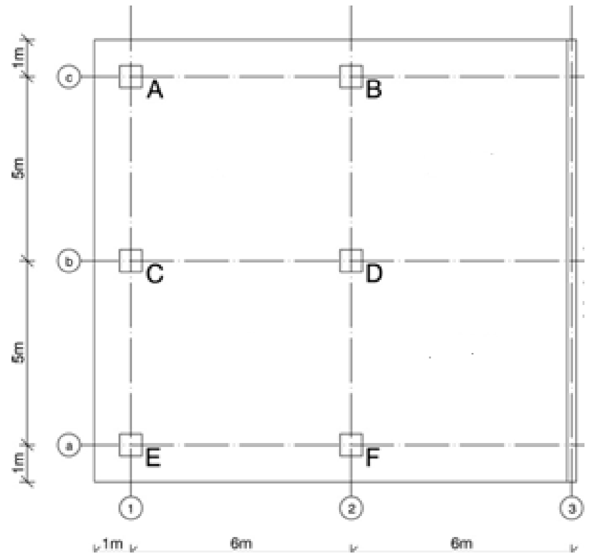

Figure 10. Representative area of the flat concrete slab

The following design parameters were given for the design:

Concrete strength class:	C 25/30
Span length	l_x = 6.00 m
Span length	l_y = 5.00 m
Cantilever length	l_{pr} = 1.00 m
Slab thickness:	h = 0.25m
Concrete cover:	c_{nom} = 20 mm
Effective depth of the cross-section:	d = 0.22 m
Cross section of all columns:	a x a = 0.30 m x 0.30 m
Acting design punching shear load – column A:	$V_{Ed,A}$ = 159.09 kN
Acting design punching shear load – column B:	$V_{Ed,B}$ = 339.96 kN
Acting design punching shear load – column C:	$V_{Ed,C}$ = 308.01 kN
Acting design punching shear load – column D:	$V_{Ed,D}$ = 608.19 kN

In order to establish the punching shear resistance above the column, a minimum flexural reinforcement is provided.

3.2 Design and detailing

The design procedure for punching shear is based on checks at the face of the column u_0 and at the basic control perimeter u_1. If shear reinforcement is required a further perimeter $u_{out,ef}$ should be calculated where shear reinforcement is no longer required.

3.2.1 Verification at the face of the column

At the column perimeter u_0, or the perimeter of the loaded area, the maximum punching shear resistance should not exceed [5]

$$V_{Ed} \leq \frac{V_{Rd,max}}{\beta} = \frac{0.4 \cdot \nu \cdot f_{cd} \cdot u_0 \cdot d}{\beta} \tag{9}$$

where v = 0.54 represents a strength reduction factor for concrete cracked in shear, f_{cd} = 16.67 N/mm² the design concrete strength and u_0 = 4a = 1.2 m the perimeter of the column. For structures where the lateral stability does not depend on frame action between the slabs and the columns, and where the adjacent spans do not differ in length by more than 25%, approximate values for β may be used [4]:

Inner column D:	β = 1.10
Edge columns B and C:	β = 1.40
Edge Column A:	β = 1.50.

With above assumptions, we have the following verifications:

Column A:	$159\ kN \leq 633\ kN$
Column B:	$340\ kN \leq 678\ kN$
Column C:	$308\ kN \leq 678\ kN$
Column D:	$608\ kN \leq 863\ kN$

3.2.2 Verification at the basic control perimeter

The basic control perimeter u_1 may be taken to be at a distance 2.0d from the loaded area and should be constructed so as to minimise its length. The length for each column is shown in Figure 11. Note that the following calculations are only conducted for column D. Only column D requires additional improvement for punching shear capacity.

Punching shear reinforcement is not necessary, if

$$v_{Ed} \leq v_{Rd,c} \tag{10}$$

The maximum shear stress should be calculated with

$$v_{Ed} \leq \beta \frac{V_{ed}}{u_{1,D} \cdot d} \tag{11}$$

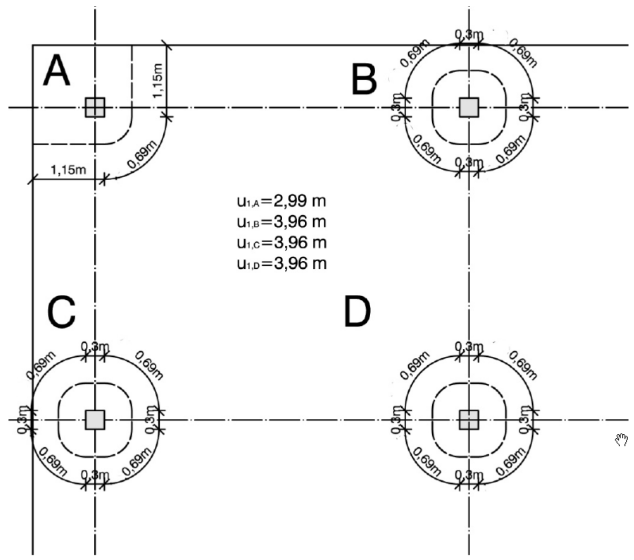

Figure 11 Length of the basic control perimeter

and the punching shear resistance of the slab without shear reinforcement in accordance with

$$v_{Rd,c} = C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{\frac{1}{3}} + \\ +k_1 \cdot \sigma_{cp} \geq v_{min} + k_1 \cdot \sigma_{cp} \tag{12}$$

where $C_{Rd,c}$ = 0.12 for flat slabs in general, the scale factor k = 1.95, the mean reinforcement ratio ρ_l in x and y direction equals 0.0052 for column D and the coefficient for inclusion of normal stresses k_1 = 0.1. The design value of the mean normal concrete stresses σ_{cp} inside the basic control perimeter are zero. The Technical Product Specifications

Z-15.1-345 [4] calculates for the minimum value of the shear resistance

$$v_{min} = 0.035 \cdot (k)^{\frac{3}{2}} \cdot \sqrt{f_{ck}} \quad (13)$$

as d is smaller than 600mm. Other values apply for different effective depths.

For column D the verification $v_{Ed} \leq v_{Rd,c}$ is not successful as shown in Eq. (14) and Eq. (15).

$$v_{Ed} = 1.1 \frac{608}{3.96 \cdot 0.22} = 0.767 N/mm^2 \quad (14)$$

$$v_{Rd,c} = 0.12 \cdot 1.95 \cdot (100 \cdot 0.0052 \cdot 25)^{\frac{1}{3}} = 0.550 N/mm^2 \quad (15)$$

Punching shear reinforcement needs to be provided.

The required number of bonded concrete screw anchors in a defined area around the column is resulting from the following two conditions

$$v_{ed} = \beta \frac{V_{ed}}{u_{1,D} \cdot d} \leq \begin{cases} v_{Rd,cs} \\ k_{max} \cdot v_{Rd,c} \end{cases} \quad (16)$$

The concrete screw anchors acting as punching shear reinforcement elements improve the punching shear capacity by up to 40%. With k_{max} = 1.4, the second condition is met, and the RELAST system can be used. RELAST system 16 with a diameter M18 is chosen and the following product parameter and limitations apply (Fig. 12):

1. first row of the bonded screw anchors shall be located between 0.3d = 6.6cm and 0.5d = 11 cm,
2. the spacing between the outer row of the bonded screw anchors and the control perimeter $u_{out,ef}$ shall not exceed 1.5d = 33 cm,
3. the radial spacing of the screw rows shall not be larger than 0.75d = 16.5 cm,
4. the spacing of the screw in the peripheral direction shall not be larger than 1.5d = 33 cm in an area inside the basic control perimeter u_1, outside not larger than 2d = 44 cm,
5. the minimum spacing is 100 mm,
6. the core diameter $d_{k,1}$ = 14.8 mm
7. the yield strength of the concrete screw anchor f_{ywd} = 434 N/mm².

The punching shear resistance with punching shear reinforcement $v_{Rd,cs}$ is calculated with

$$v_{Rd,cs} = 0.75 \cdot v_{Rd,c} + 1.5 \cdot \frac{d}{s_r} \cdot A_{SW} \cdot f_{ywd,ef} \cdot \frac{1}{u_1 d} \quad (17)$$

where the allowable cross-section area of the punching shear reinforcement in one row around the column is the minimum of

$$A_{SW} = min \begin{cases} A_{SW,i} \\ \frac{A_{SW,1.5d}}{1.5 \cdot d} \cdot s_r \end{cases} \quad (18)$$

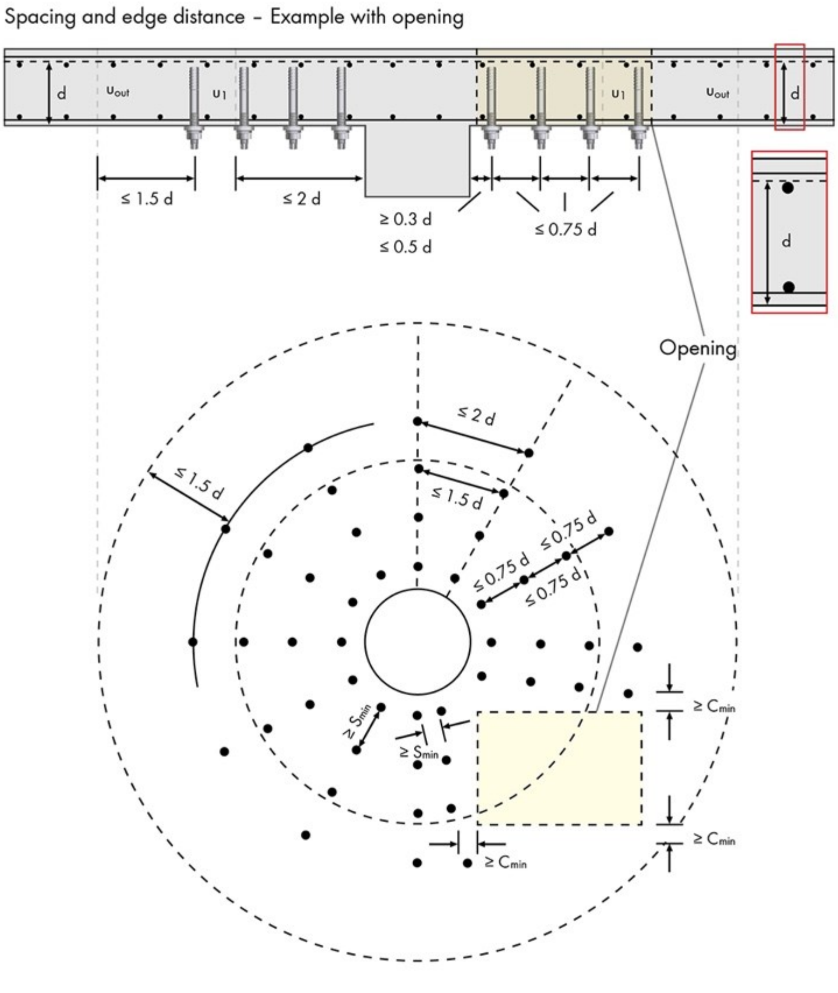

Figure 12. Geometrical limitations

For the verification we chose 5 rows with a radial spacing of s_r = 15 cm and 12 anchors per row. The spacing of the first row to the column equals 10 cm. The cross section area in any row around the column is $A_{sw,i}$ = 20.64 cm². The entire cross sectional area between 0.3d = 6.6 cm and 1.5d= 33 cm calculates from the cross section of 3 rows $A_{SW,1.5d}$ = 61.92 cm² and A_{SW} = 20.64 cm² .

The design value of the active stress in the punching shear reinforcement is calculated with

$$f_{ywd,ef} = 5.5 \cdot \frac{k_{max}}{\gamma_s} \cdot \frac{d}{d_{k,1}} = 5.5 \cdot \frac{1.4}{1.15} \cdot \frac{22}{1.48} = = 99.53 N/mm^2 \leq 217 N/mm^2 \quad (19)$$

The punching shear resistance with punching shear reinforcement equals $v_{Rd,cs}$ = 0.93 N/mm² and successfully verified as it is greater than the acting shear of v_{Ed} = 0.77 N/mm².

The perimeter $u_{out,ef}$, where shear reinforcement is no longer required is calculated with

$$u_{out,ef} = \beta \frac{V_{ed}}{v_{Rd,c} \cdot d} = \frac{1.1 \cdot 608}{550 \cdot 0.22} = 5.52m \quad (20)$$

which equals an outer radius $r_{out,ef}$ = 88 cm.

For the above calculated 60 bonded concrete screw anchors of the RELAST system 16 with a metric thread M18, the rules for the geometrical composition are successfully checked.

1. the first row of the bonded screw anchors is located at 10cm from the column which is between the required 0.3d = 6.6 cm and 0.5d = 11 cm. The respective radius r_a equals 25cm,
2. the perimeter of the first row equals 157 cm which makes with 12 screw anchors a spacing of 130.9 mm which is greater than the required minimum spacing of 100 mm.
3. the radial spacing of 15 cm is less than the required 0.75d = 16.5 cm,
4. the length of the basic control perimeter equals 339cm and is filled with 12 anchors at spacings of 28.25 cm in the peripheral direction which is less than 1.5d = 33 cm, the last row of the 5 radial rows has a radius r_{out} = 85 cm and gives a spacing of 3 cm to $r_{out,ef}$ = 88cm, which does not exceed required maximum spacing of 1.5d = 33 cm
5. the perimeter length of the last row equals 534 cm and is filled with 12 anchors at spacings of 44.0 cm in the peripheral direction which is lesser than 2d = 44 cm.

Each bonded concrete screw anchor is installed with a embedment depth of h_{nom} = 160 mm and provides a minimum for the projected thread length of $t_{üb}$ ≥ 47 mm to accommodate the big washer, the wedge-lock spring washer and the nut.

4 Summary

The two design examples show that the RELAST system improves the shear or punching shear capacity with a practicable number of bonded concrete screw anchors. The number of screws is not much different from the number of cast-in shear or punching shear reinforcement which would have been provided for a new structure. Thus, the provided solution is economically feasible and provides additional benefits from having to access only the soffit of the structure for installing the system. In many cases, occupancy could continue in the area above where RELAST installation is being done.

The design approach utilizes existing formulas of an established European Code, and provides modification parameters as necessary. As the design does not take existing shear and punching shear reinforcement into account, the described approach can be used when codes do not provide the same level of detail and guidance in the design.

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