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## Post-installed retrofitting system for improving the punching shear and shear capacity of reinforced concrete elements

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### ABSTRACT

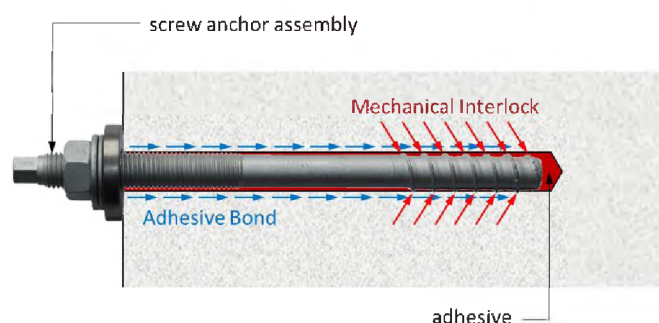
*Finding appropriate strengthening solutions for existing reinforced concrete (RC) elements is always a challenge for structural engineers. Additional load capacity may be needed as the change of type of occupancy and more restrictive design standards require higher load levels or different detailing of reinforcement. Growing traffic volume would be a main topic in bridge design. This affects very often the shear and the punching shear and its reinforcement level.*

*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 DIBt with a National Technical Approval. The 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 life time 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. Demolition of old structures, and building a new one is no longer the only feasible option.*

## THE POST-INSTALLED RETROFITTING SYSTEM

### 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.



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

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 AS 5216:2018 or 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 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. AS3600:2018 unfortunately does not provide the same level of guidance for punching shear design as its European counterparts.

### 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:

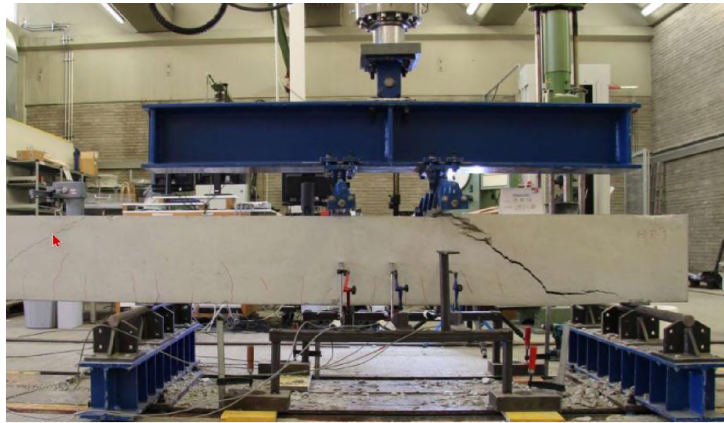
1. characteristic resistance to tension or shear,
2. sensitivity to different installation and service temperatures,
3. freeze/thaw conditions,
4. increased concrete crack width,
5. crack cycling under load,
6. repeated loads,
7. sustained loads,
8. various environmental exposure such as high alkalinity 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 roughly 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.).



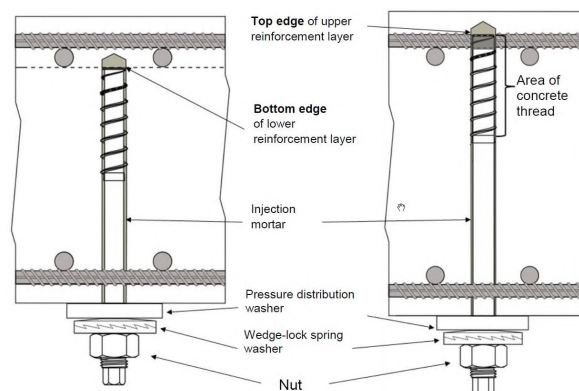
**Figure 2. Large Scale Shear tests.** "(Feix et. al. 2019a)"



**Figure 3. Large Scale Punching Shear tests.** "(Feix et. al. 2019a)"

#### **Laboratory Tests Related to the Shear Capacity**

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



**Figure 4. Optional Installation Conditions.**

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

Three pulsating load tests were conducted to evaluate the performance of retro-fitted beams under  $5 \times 10^6$  load cycles. The amplitude of the load applied, has a lower bound equal to one-third of the static ultimate load and the upper bound is two-thirds of the static ultimate load. No failure was identified.

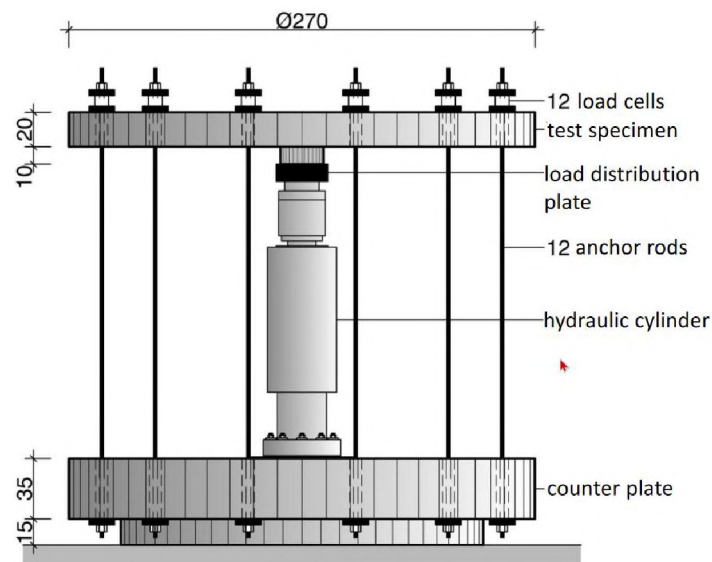
The test setup and the results are described in detail by Lechner in "(Feix et. al. 2020b)". The results

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 “(DIBt 2019a)”.

### **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).



**Figure 5. Test Setup for the Punching Shear Capacity Tests.** “(Feix et. al. 2020b)”

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 ratio of the longitudinal reinforcement to the punching shear performance of the test specimen.

Pulsating loads on the retro-fitted slab with  $2 \times 10^6$  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 two-thirds of the static ultimate load, did not result in visual signs of damages. 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 “(Feix et. al. 2020b)”. Summarily the retro-fitted component achieved up to 40% punching shear capacity improvement compared to components without punching 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-15.1-345, published in October 2019 “(DIBt 2019b)”.

### **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. AS5216:2018 and AS3600:2018, unfortunately, does not provide the same level of detail and guidance in the design of post-installed punching shear reinforcement. While this seems undesirable, the National Construction Code provide the ‘performance route’ in dealing with post-installed punching shear reinforcement. As such the said European approach may be implemented to a level that satisfies Australian 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 have 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 minimum concrete thickness of 200mm to observe. In case of punching shear retrofitting, the RELAST system is only applicable 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 DIN EN ISO 9223 and service temperature between  $-40^{\circ}\text{C}$  to  $80^{\circ}\text{C}$ . 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.

## IMPROVING THE SHEAR CAPACITY

### 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.



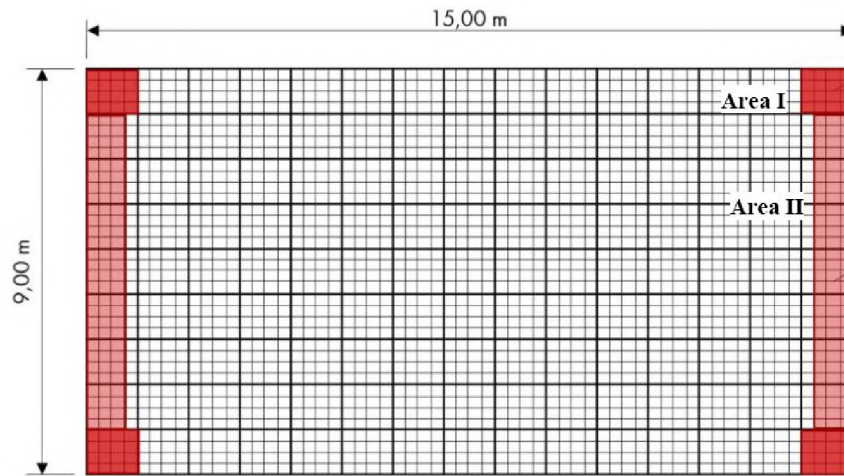
Figure 6. Single-span Concrete Slab Bridge.

The following design parameter are given for the design:

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

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

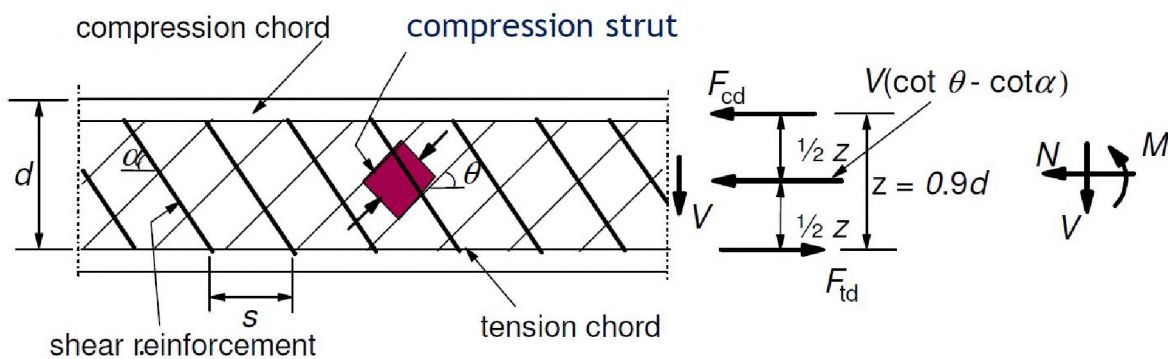
Acting design shear load Area I:	$V_{\text{Ed,max,I}} = 500\text{kN/m}$
Acting design shear load Area II:	$V_{\text{Ed,max,II}} = 300\text{kN/m}$



**Figure 7. Various Areas of the Single-span Concrete Slab Bridge.**

### Design and Detailing

The design of members with shear reinforcement is based on a truss model (Fig. 8), in which we take  $\alpha = 90^\circ$  and  $\theta = 45^\circ$  and as given, the inner lever arm with  $z = 0.9d = 0.414\text{m}$  and the minimum width of the compression chord  $b_w = 1\text{m}$ .



**Figure 8. Truss Model. “(DIN 2011-Fig.6.5)”**

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 the task of the cast-in shear reinforcement.

### Verification of the Compression Strut

The resistance of the compression strut “(DIN 2011-(6.9))”, “(DIBt 2019a)”

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

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 “(DIBt 2019a)” and “(DIN 2011)”, the maximum permissible spacings from table 1 must be taken into account

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

**Table 1. Maximum permissible spacings. “(DIBt 2019a)”**

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

### Verification of the Tension Tie

The resistance of the tension tie is calculated with “(DIN 2011-(6.8))”, “(DIBt 2019a)”

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

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

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

and the ratio of cross section for improving the shear capacity

$$a_{sw} = \frac{A_{sw,sc}}{s_1 \cdot s_t} \quad (5)$$

For the further verification we choose the RELAST system 22 with a diameter M20. The selected longitudinal spacing  $s_1 = 0.30m$  and transverse spacing  $s_t = 0.30m$  are below their respective maximum allowed values.

The material parameter are given in table 2 “(DIBt 2019a)”

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/mm <sup>2</sup>
<b>Würth RELAST 22</b>	M20	24.3	20.5	16.93	500

**Table 2. Dimensions and Material of the Concrete Screw Anchor. “(DIBt 2019a)”**

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  $a_{sw} = 36.67cm^2/m^2$  or the relative ratio to  $\rho_{sw} = 0.36\%$ .

With the second load factor  $c_2 = 0.046$  and the first load factor  $c_1 = 0.2384$  according to table 5 in “(DIBt 2019a)” 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  $f_{ywd,ef} = 369.91N/mm^2 \leq 434.78N/mm^2$ .

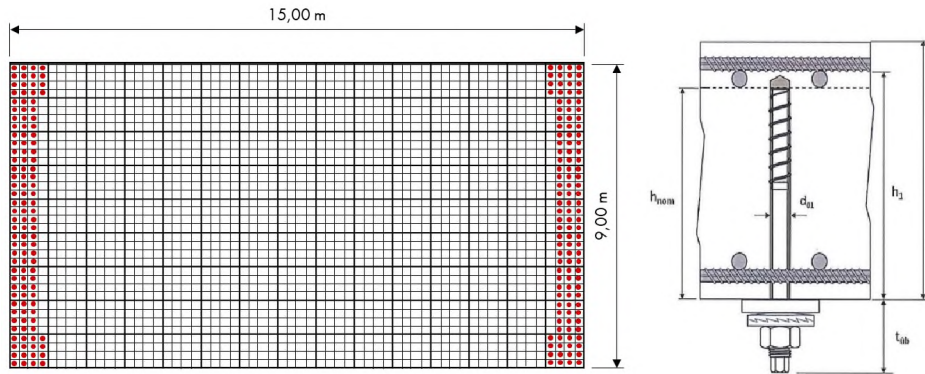
The required cross section of the screws to verify successfully the tension tie in area I is

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

and to verify successfully th tension tie in area II

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

The installation plan of Figure 8 shows the screw with the respective selected longitudinal spacing  $s_l = 0.30\text{m}$  and transverse spacing  $s_t = 0.30\text{m}$  for area I and II, and an edge distance of  $c = 0.15\text{m}$  where it applies.



**Figure 8. Installation Plan and Installed Bonded Concrete Screw Anchor.**

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

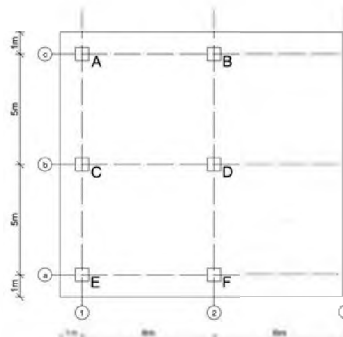
### IMPROVING THE PUNCHING SHEAR CAPACITY

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, at a relatively quicker time, while the structure remains operational.

#### 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 9.





**Figure 9. Representative Area of the Flat Concrete Slab.**

The following design parameters are given for the design:

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

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

### 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.

#### Verification at the Face of the Column

At the column perimeter  $u_0$ , or the perimeter of the loaded area, the maximum punching shear stress should not be exceed "(DIN 2011)"

$$V_{Ed} \leq \frac{V_{rd,max}}{\beta} = \frac{0.4 \cdot v \cdot f_{cd} \cdot u_0 \cdot d}{\beta} \quad (9)$$

where  $v = 0.54$  represents a strength reduction factor for concrete cracked in shear,  $f_{cd} = 16.67\text{N/mm}^2$  the design concrete strength and  $u_0 = 4a = 1.2\text{m}$  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  $\beta$  may be used "(DIBt 2019b)":

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

With above assumptions, we have the following verifications:

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

#### 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

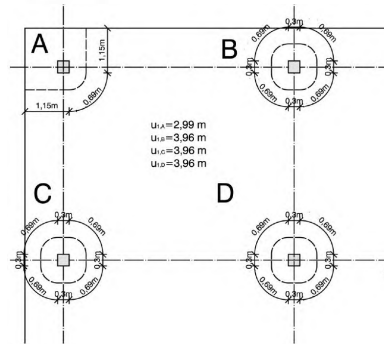
constructed so as to minimise its length. The length for each column is shown in Figure 10. Note that the following calculations are only conducted for column D. Only column D requires additional improvement for punching shear capacity.

Punching shear reinforcement is not necessary, if

$$v_{Ed} \leq v_{rd,c} \quad (10)$$

The maximum shear stress should be calculated with

$$v_{Ed} \leq \beta_{u_{1,D}} \frac{V_{ed}}{d} \quad (11)$$



**Figure 10. Length of the Basic Control Perimeter.**

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

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

where  $C_{Rd,c} = 0.12$  for flat slabs in general, the scale factor  $k = 1.95$ , the mean reinforcement ratio  $\rho_l$  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  $\rho_{cp}$  inside the basic control perimeter are zero. The Technical Product Specifications Z-15.1-345 “(DIBt 2019b)” calculates for the minimum value of the shear resistance

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

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

For column D the verification  $v_{1;d} \leq v_{Rd,c}$  is not successful as shown in Eq. (14) and Eq. (15).

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

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

Punching shear reinforcement need 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

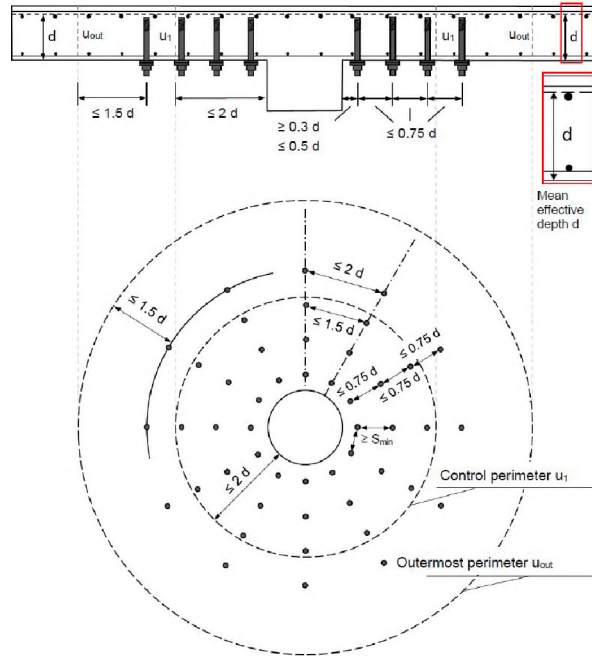
$$v_{ed} = \beta_{u_{1,D}} \frac{V_{ed}}{d} \leq \left\{ \begin{array}{l} v_{Rd,cs} \\ k_{max} \cdot v_{Rd,c} \end{array} \right. \quad (16)$$

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. 11):

1. first row of the bonded screw anchors shall be located between  $0.3d = 6.6\text{cm}$  and  $0.5d = 11\text{cm}$ ,
2. the spacing between the outer row of the bonded screw anchors and the controll perimeter  $u_{out,ef}$

shall not exceed  $1.5d = 33\text{cm}$ ,

3. the radial spacing of the screw rows shall not be larger than  $0.75d = 16.5\text{cm}$ ,
4. the spacing of the screw in the peripheral direction shall not be larger than  $1.5d = 33\text{cm}$  in an area inside the basic control perimeter  $u_1$ , outside not larger than  $2d = 44\text{cm}$ ,
5. the minimum spacing is  $100\text{mm}$ ,
6. the core diameter  $d_{k,1} = 14.8\text{mm}$
7. the yield strength of the concrete screw anchor  $f_{ywd} = 434\text{N/mm}^2$ .



**Figure 11. Geometrical limitations**

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

$$A_{SW} = \min \left\{ \frac{A_{SW,i}}{1.5 \cdot d} \cdot s_r \right\} \quad (18)$$

For the verification we choose 5 rows with a radial spacing of  $s_r = 15\text{cm}$  and 12 anchors per row. The spacing of the first row to the column equals  $10\text{cm}$ . The cross section area in any row around the column is  $A_{SW,i} = 20.64\text{cm}^2$ . The entire cross section area between  $0.3d = 6.6\text{cm}$  and  $1.5d = 33\text{cm}$  calculates from the cross section of 3 rows  $A_{SW,1.5d} = 61.92\text{cm}^2$  and  $A_{SW} = 20.64\text{cm}^2$ .

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

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

The punching shear resistance with punching shear reinforcement equals  $v_{Rd,cs} = 0.93\text{N/mm}^2$  and successfully verified as it is bigger than the acting shear of  $v_{Ed} = 0.77\text{N/mm}^2$ .

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

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

which equals a outer radius  $r_{out,ef} = 88\text{cm}$ .

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

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

### 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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