Concrete screws as a post-installed punching reinforcement

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Abstract
A major part of central European infrastructure buildings was designed decades ago and has different needs of strengthening. Increasing traffic volume, increasing axle loads, and a growth in transport volume as well as more restrictive design rules are the reasons why the support regions of existing bridges and flat slabs often show a lack of punching resistance today. At the University of Innsbruck, a system for subsequent strengthening by the use of concrete screws was developed. Various laboratory tests showed that the system leads to a significant increase of punching resistance with minimal efforts for its installation. This article deals with the development of a numerical model that can predict the punching loads of unstrengthened and screw-strengthened punching plates. Further the punching loads from the laboratory tests and the simulations are compared to the predictions of a design approach. The presented novel design approach is an advancement of the existing Eurocode 2 provisions and allows the influence of the screws on the punching resistance to be taken into account. The comparison shows that the numerical model predicts the punching resistances in an appropriate way and the design approach predicts them on the safe side. The presented design approach was included into the technical assessment for the concrete screws of the system reLAST as post-installed punching reinforcement system [Z-15.1-340 (2019)] in order to be applicable in practice.

Keywords
concrete screws, design approach, numerical simulation, punching, punching shear reinforcement, shear reinforcement, strengthening

1 INTRODUCTION
The strengthening and restoration of existing structures gains more and more importance as a field of civil engineering. For structures made of reinforced concrete the punching resistance is of vital importance. The inspections and recalculation of existing bridges and slabs have revealed that their support areas often show a lack...
of shear punching resistance. The main reasons for such structural deficits are the age of the infrastructure buildings, \(^2\) changed requirements, loads and codes as well as poor maintenance. \(^3\)–\(^5\)

Conventional methods for the subsequent increase of the punching resistance are associated with great effort and high costs and usually the accessibility of the upper surface of the structure. \(^6\)–\(^11\) Therefore, restricted operation and expensive detail solutions for the rearrangement of the structures sealing arise. In contrast, the use of concrete screws from the system reLAST\(^{©}\) 12 as a subsequently installed punching reinforcement is a technically innovative, resource-saving, and economically effective solution. \(^13\)–\(^16\) A concrete screw is a fastening system made of steel and is equipped with two types of threads for anchoring. On one side the concrete screws have a self-tapping thread to cut a convolution into the walls of predrilled holes in the concrete to create an interlocking connection between the screw and the concrete. Adhesive agent can be used to fill the gap between the screw and the concrete for additional capacity of the connection and as a sealing of the borehole. On the other end of the screw is an ISO-metric connection thread to anchor the loads on the surface by the use of a hexagonal nut, a wedge locking washer, and a packing plate. Hence it is not necessary to drill through the structure and anchor on the opposite side. Therefore, no restrictions of the traffic occur. Furthermore, road surfaces, ballast beds, and sealings remain untouched. The screws are arranged concentrically around the column as a post-installed punching reinforcement to increase the punching resistance. As the shear cracks develop under rising load, the screws transfer the arising forces over the cracks. In Lechner and Feix, \(^17\) it is shown that the very same system can be used as a subsequent shear strengthening for concrete beams.

To investigate the efficiency and effectivity of the new system and to prove its suitability for the strengthening of bridges punching tests on screw-strengthened plates were performed at the University of Innsbruck. The test results were published in Wörle \(^3\) and Walkner et al. \(^18\) This article deals with the numerical simulation of the performed tests as well as with a developed design approach. The objective of such simulations is the prediction of the ultimate loads of punching plates. Such simulations allow it to perform time-saving predictions on punching loads and to run numerical parameter studies without performing expensive and complex laboratory tests. A model that takes all the complex behavior of the punching area as well as the screws into account is essential for good predictions. As the punching area is stressed simultaneously by high shear forces and bending moments and the screws are placed in this very area 3d-modeling is used to describe the plate. The 3d-model allows the contribution of the screws to the punching resistance to be taken into account and can account for the bond behavior of the screws and the nonlinear behavior of the cracked concrete.

Various publications deal with the punching problem. The numerical simulation of punching plates and their ultimate loads is examined in Kadlec and Cervenka. \(^19\) Information on model uncertainties and modeling characteristics for punching plates can be found in Kadlec et al. \(^20\) The comparison between laboratory punching tests and numerical simulations are discussed in Faria et al. \(^21\) Genikomsou and Polak \(^22\) provide a comparison between punching plates with different shear reinforcement ratios and different arrangements of shear reinforcement.

### 2 | EXPERIMENTAL INVESTIGATIONS

The punching tests were performed in four test series with 21 circular specimens with a diameter of 270 cm and a thickness of 20 cm. The column stub was 10 cm high and its diameter was 30 cm for series 2011 and 25 cm for the series 2016, 2017, and 2018. The test setup and specimens are shown in Figure 1. The first test series was performed in 2011 and is described in Feix et al. \(^13\) and Wörle. \(^23\) The aim of the four performed tests carried out in this series was to show the basic suitability of concrete screws as post-installed punching reinforcement. The series showed that the punching resistance can be increased by more than 50% with the used strengthening configuration. The series also showed that the use of adhesive agent increases the strengthening effect and that the reduction of the screw diameter from 22 to 16 mm means a reduction of the strengthening capacity. A more detailed description of the series can be found in Feix et al. \(^13\) and Wörle. \(^23\)

The second test series from 2016 \(^18\) showed that an installation of the screws to the upper side of the flexural reinforcement as shown in Figure 3 leads to a less brittle failure mode than the installation to the lower side of the flexural reinforcement. As the amount of flexural reinforcement contributes to the punching resistance it is of vital importance to prevent any damage to the bars by the drilling process. However, the predictability of the location of the reinforcement bars decreases with increasing plate thickness. Therefore, the configuration with screws installed to the lower side of the flexural reinforcement represents the conservative case that no screw can be installed to the upper side without damaging the flexural reinforcement. The reduction of the installation
depth to the lower side of the flexural reinforcement causes a reduction of only 2% of the punching load compared to the installation to the upper face of the flexural reinforcement. The failure mode remains almost as brittle as for the unstrengthened plates. The results of test series 2017 showed that a cyclic pre-loading on a realistic load level according to the fatigue load level for road bridges according to ÖNORM EN 1991-2 has no negative impact on the strengthening effect. Furthermore, omitting the outermost (fourth) screw ring has no negative effects on the strengthening capacity. The fourth test series was performed in 2018 and showed that an increase of the degree of flexural reinforcement leads to an increase of the strengthening effect while the deformation capacity of the plate decreases. The increasing of the amount of shear reinforcement (number of screws) leads to an increase of the strengthening effect and the deformation capacity. This effect gets stronger the higher the rate of flexural reinforcement is. For low ratios of flexural reinforcement a bending failure might become decisive. The increase of the number of screws leads to an increase of deformation capacity, but it has no further strengthening effect.

3 | NUMERICAL INVESTIGATIONS

For the simulation of selected test configurations the program ATENA (ATENA GID version 13.0.2) was used to create numerical models of the punching plates. To simulate the strengthened plates a screw model is implemented. The laboratory tests are indicated with Sxx-Pyy hereafter. Whereby S stands for test series, xx for the number of the test series, P for plate, and yy for the number of the particular specimen.

3.1 | Modeled tests

All modeled plates with post-installed screws were equipped with TSM-B22-M20 screws. The number after letter B in the denotation of the screws describes the borehole diameter in millimeter. The number after letter M stands for the diameter of the ISO-thread. The last number as shown in Figures 2–4 describes the length of the concrete screws in millimeter. Hereafter, the screws will be referred to as TSM-B22. Figure 2 shows the modeled plates from series 2016. All plates from series 2016 and 2017 were modeled with flexural reinforcement in the tension zone with 16 mm diameter and a space of 9 cm.

Three plates were modeled from series 2017. For the numerical simulation the cyclic pre-loading of S02-P06 was neglected. The modeled plates of series 2017 are shown in Figure 3.

From series 2018 all six laboratory tests shown in Figure 4 were modeled. The investigated reinforcement ratios were 1.37% for S03-P01 and S03-P02 (diameter 16 mm, spacing 9 cm), 1.04% for S03-P03 and S03-P04 (diameter 14 mm, spacing 9 cm), and 0.77% for S03-P05 and S03-P06 (diameter 12 mm, spacing 9 cm).

3.2 | Basic model

3.2.1 | General modeling

The modeled punching plate shown in Figure 5 consists of plate, column stub, reinforcement, anchor plates, and load distribution plate. For the strengthened plate screws are added as post-installed punching reinforcement according to Figure 9. The modeling of the screws will be discussed later in the article. To reduce the required computation capacity the symmetry of the geometry and the load of the punching plate were taken into account. Therefore, only a quarter of the plate was modeled. The symmetry was considered according to Figure 5 by fixing the symmetry-planes in the orthogonal directions with...
the conditions $u_y = u_r = 0$ for the $y$-$z$-plane and $u_x = u_r = 0$ for the $x$-$z$-plane. For further reduction of the required computational resources linear-elastic material was assigned to the column stub, to the anchor plates, and to the load distribution plate (see Figures 1 and 5). The material model used to simulate the behavior of the concrete is SBETA which is implemented in ATENA. It is able to consider the cracking of concrete under tension loads as well as the nonlinear behavior under compression. Furthermore, it uses a biaxial stress failure criterion for the concrete, considers tension stiffening effects as well as the reduction of the compression strength and the shear strength due to cracking. A detailed description of the material model can be found in Cervenka et al.\textsuperscript{25} and Cervenka and Bergmeister.\textsuperscript{26}

The calibration of the basic model is based on the two unstrengthened tests S01-P00 and S01-P04\textsuperscript{18} from Figure 2. The averaged test is indicated as S01-P00P04 and its numerical counterpart is indicated as N01-P00P04.

3.2.2 | DETERMINATION OF THE MESH SIZE AND THE ELEMENT TYPE

Depending on the investigated problem several element types are implemented into ATENA. For the meshing of the described punching plate hexahedral elements and tetrahedral elements were used. Hughes\textsuperscript{27} stated that the correct choice of the element can influence the numerically predicted stiffness of a specimen as well as its ultimate load. Especially tetrahedral elements tend to overestimate the stiffness. This effect is called shear locking.\textsuperscript{28} Therefore, the punching plate was meshed with 8-noded isoparametric, gauss-integrated hexahedral elements of the type CCIsoBrick. A structured mesh was assigned to the plate because the implemented mesh generator is offering structured mesh for cuboid volumes only. The column stub, the anchor plates, and the load distribution plate were meshed unstructured with tetrahedral elements, since their influence on the stiffness of
the overall system is of minor significance. Figure 5 shows the meshed basic model. To take shear stresses correctly into account at least 4–6 elements should be used to model the plates thickness. A parameter study showed that the behavior of the plate can be modeled close to reality with elements of 20 mm side length.

### 3.2.3 Modeling the concrete and the reinforcement

ATENA calculates the material parameters for the concrete depending on the compression strength. By adding more measured parameters the description of the concrete used in the laboratory can be made more accurate. ATENA defines the behavior of the compressed concrete by the volume parameter and the plastic deformation. The tension behavior is characterized by linear-elastic behavior if the tensile strength is not reached. When the tension exceeds the tensile strength, the behavior is characterized by crack formation in the process zone. ATENA uses the concept of smeared cracks to take the crack effects into account. The fixed crack model and the rotated crack model are both implemented into ATENA. For the simulation of the punching plates, the fixed crack model was used.

The first simulations of the punching plates showed an overestimation of the punching load. The transition from the uncracked to the cracked state of the concrete took place at load higher than in the tests as well. The earlier crack formation in the test is due to tensile stresses in the plate resulting from shrinkage prevented by the reinforcement. Residual stresses caused by temperature can be named as another reason. The modulus of elasticity and the tensile strength have an effect on the stiffness of the plate too. With increasing modulus of elasticity, the stiffness increases as well. The modulus of elasticity was estimated from the compression strength measured in the laboratory. The tensile strength is a far more scattering parameter than the compression strength. It can be derived by tension split testing. Closely linked to the tensile strength is the fracture energy which can be derived from uniaxial tensile testing or the three-point bending test. The fracture energy is the

### Table: Numerical investigated strengthening configurations from series 2018

| Configuration | Description |
|---------------|-------------|
| S03-P01       | 24 TSM-B22-M20-335 mm |
| S03-P02       | 36 TSM-B22-M20-335 mm |
| S03-P03       | 24 TSM-B22-M20-335 mm |
| S03-P04       | 36 TSM-B22-M20-335 mm |
| S03-P05       | 24 TSM-B22-M20-335 mm |
| S03-P06       | 36 TSM-B22-M20-335 mm |

### Figure 5 Components and mesh of the punching plate
parameter that is used to define the tension behavior in constitutive model of the concrete.

According to Table 3.1 in ÖNORM EN 1992-1-1\textsuperscript{30} the tensile strength \( f_t \) was calculated from the mean cylinder strength \( f_{cm} \) with Equation (1). The fracture energy was calculated from the basis value \( G_{f0} \) according to the largest grain diameter \( d_{max} \) and the mean cylinder strength \( f_{cm} \) with Equation (2) from Model Code 90.\textsuperscript{31}

\[
f_t = 0.3 \left( f_{cm} - 8 \text{ MPa} \right)^{2/3}. \tag{1}
\]

\[
G_f = G_{f0} \left( \frac{f_{cm}}{10} \right)^{0.7} \quad \text{with } G_{f0} = 30 \text{ Nm/m}^2 \text{ for } d_{max} = 16 \text{ mm.} \tag{2}
\]

In reference to the recommendations from Pryl and Cervenka,\textsuperscript{29} the tensile strength and the fracture energy were slightly reduced for the present model to generate a material behavior similar to concrete tested in the laboratory. Figure 6 compares the load–displacement curves of the unstrengthened laboratory tests and variations of the two parameters tensile strength and fracture energy. Both, the tensile strength and the fracture energy, were reduced by 20%. This approach leads to satisfying results for the predicted punching loads as well as for the shape of the curve and the propagated shear crack pattern.

ATENA offers the possibility to model the reinforcement discrete or smeared. The discrete modeling can be done with truss elements or with 3d elements. To consider bond behavior with the 3d elements the plate would have to be divided into a lot of elements along the vertical axis. For the punching plate, the truss elements seem to be more appropriate as they have only axial stiffness and are therefore far less time consuming in numerical processing. The connection between the reinforcement and the concrete can be defined as fixed contact or with a bond–slip relationship. The fixed connection tends to lead to an overestimation of the concrete members stiffness. The consideration of the bond–slip behavior requires more computing power. ATENA uses the bond-law according to Model Code 2010.\textsuperscript{32} It describes the bond–slip relationship by defining the bond-strength which is scaled along the truss element to generate the wanted bond behavior.

Figure 7 shows the modeled reinforcement of the punching plate. It was defined as reinforcement with Austrian classification B550\textsuperscript{33} with bilinear behavior.
and strain hardening. Between the reinforcement bars and the concrete slip according to Model Code 2010 was assumed. The bent-up bar ends of the flexural reinforcement were not modeled. The stiffness of the punching plate is influenced by the location of the bending reinforcement, its diameter, and its modulus of elasticity. The location of the reinforcement was checked in the laboratory before the pouring as well as by saw cuts afterwards. The documented location was used for the definition of the parameters for the simulation.

3.3 | Modeling of the screw

The screws used in the laboratory tests were corresponding to the assessments 018-2101#022-(031/13-ZUL): 2015 and Z-15.1-340.

To generate a screw model which is able to represent the behavior of the real screw as good as necessary it is of significant importance to define the bond–slip relationship between the screw and the concrete. To keep the necessary computing power in an acceptable range some simplifications have to be made. The database for creating a bond–slip law in ATENA was derived from laboratory tests. In Lechner et al. the bond–slip behavior of the used screws was examined by pull-out tests for the two different cube compressive concrete strengths listed in Table 1. The strengths of the concretes used in the punching tests were derived from test-cubes and test-cylinders and differ from those of the pull-out tests. Table 3 shows the strengths derived from the punching tests. For the performed pull-out tests the TSM-B22 screws were installed with adhesive agent and were then loaded with narrow support until pull out failure occurred.

As the pull-out tests were performed for two concrete strengths, only the bond–slip relations for the concrete strength of the punching tests had to be interpolated from the known curves of the concretes B3 and B6 in Table 1. For each punching test series one pull-out curve was interpolated between the experimentally determined curves of the concretes B3 and B6 using the smallest concrete strength of the respective test series. In the absence of more detailed data a linear interpolation was used. Figure 8 shows the pull-out curve for series 2016 exemplarily. The compressive strength of test S01-P01 ($f_{\text{cm,cube}} = 40.7$ MPa) was used for its interpolation. Table 2 shows the bond-strengths for the three test series.

For series 2018 the cube compressive strength of test S03-P01 was 48.5 MPa and exceeded the strength of concrete B6. Therefore, no assured results for the bond–slip behavior were known for this strength range. An extrapolation seemed not to be useful to generate the pull-out curve from the curves of B3 and B6. For the pull-out behavior of the screws in this series, the pull-out curve of concrete B6 was used. As the screws are strained on a low level and the stiffnesses of the pull-out curves differ only slightly, this assumption seems to be reasonable. The determined bond-strengths for the screw models are listed in Table 2.

| Test          | Mean value (MPa) |
|--------------|-----------------|
| Compression strength concrete B3 | 22.10 |
| Compression strength concrete B6 | 43.94 |

Table 2 Bond-strength for the definition of the screw models

| Test series | Bond-strength $\tau_{\text{max}}$ (MPa) |
|------------|---------------------------------|
| Series 2016 | 23.34 |
| Series 2017 | 21.09 |
| Series 2018 | 25.72 |

Figure 8 Interpolation of the pull-out behavior for series 2016
In ATENA the screws were defined as truss elements with axial stiffness only. It is assumed that the bond is transferred by the 10 cm long self-cutting thread only while the shaft of the screw is assumed to be smooth and unbonded. This assumption is reasonable for thin plates. Figure 9 shows a schematic sketch of the screw model implemented into the punching plate. Between the packing plates and the concrete surface a fixed contact is defined. The truss element is anchored with a fixed-end contact in the packing plate and with a non-fixed contact in the punching plate. Table 3 shows the input values for the numerical simulations of the punching tests.

### Table 3: Input values for the simulations

| Year | Test ID   | \(f_c\) (MPa) | \(f_{ct}\) (MPa) | \(G_f\) (MN/m) | Assumed in simulation |
|------|-----------|---------------|-----------------|----------------|----------------------|
| 2016 | S01-P00  | 33.40         | 2.59            | 7.0e-5         | 2.07 5.6e-5         |
|      | S01-P01  | 32.17         | 2.51            | 6.8e-5         | 2.01 5.4e-5         |
|      | S01-P02  | 32.90         | 2.56            | 6.9e-5         | 2.05 5.5e-5         |
|      | S01-P03  | 33.13         | 2.57            | 6.9e-5         | 2.06 5.6e-5         |
| 2017 | S02-P01  | 28.56         | 2.25            | 6.3e-5         | 1.80 5.0e-5         |
|      | S02-P02  | 28.16         | 2.22            | 6.2e-5         | 1.78 5.0e-5         |
|      | S02-P01 3R | 28.56       | 2.25            | 6.3e-5         | 1.80 5.0e-5         |
| 2018 | S03-P01  | 41.13         | 3.09            | 8.1e-5         | 2.47 6.5e-5         |
|      | S03-P02  | 40.17         | 3.03            | 7.9e-5         | 2.42 6.4e-5         |
|      | S03-P03  | 40.63         | 3.06            | 8.0e-5         | 2.45 6.4e-5         |
|      | S03-P04  | 41.03         | 3.09            | 8.1e-5         | 2.47 6.5e-5         |
|      | S03-P05  | 42.33         | 3.17            | 8.2e-5         | 2.54 6.6e-5         |
|      | S03-P06  | 41.87         | 3.14            | 8.2e-5         | 2.51 6.5e-5         |

Note: The transition between the uncracked and the cracked state takes place at a load higher than in the laboratory tests. To describe the behavior of the plate in a better way the calculated tensile strength and the fracture energy (column 4 and 5) were adjusted (column 6 and 7).

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### 3.4 Results

Comparing the punching loads of the laboratory tests with those of the simulations it can be emphasized that they match very well. Figure 10 shows the load–deformation curves of the unstrengthened tests S01-P00 and S01-P04 as well as their mean values and the curve from simulation N01-P00P04. The punching loads of the unstrengthened plates differ between 677 and 720 kN. With 724 kN the simulation approximates to the test very well and reaches 103.6% of the mean punching load of 699 kN from the laboratory tests. The figure on the right side of Figure 10 shows the load deformation curve for S01-P01 as well as its simulation and is representative for the results of the simulations of the strengthened tests. The simulation of S01-P01 reaches a punching load of 887 kN. With 103.4% it approximates to the laboratory punching load of 858 kN very well. The stiffness of the plates exceeds the laboratory values and therefore the deformations are underestimated.

In Figure 11 the saw cuts of the real plates are compared to the simulations of the two tests. The cuts show the principal strains along the y-axis of the plate. The simulation approximates to the shear crack in an appropriate way. The inclination of the simulated crack is a little bit too steep for the unstrengthened simulation. For the strengthened test the shear crack as well as its progress along the flexural reinforcement can be simulated well.

The results of all numerical simulated laboratory tests are shown in Table 4. The correlation between the tests and the simulations is represented by the model uncertainty \(\Theta\) which is defined as the ratio between the laboratory punching load \(V_{test}\) and the simulated load.
Table 4 shows that this model uncertainty is close to 1.0 for all simulations. Thus, the punching loads are approximated very well by the described numerical model. Figure 14 illustrates the results by comparing the punching loads of the laboratory tests and the simulations as well as the loads derived from a design approach.

Figures 10 and 11 and Table 4 show that the described numerical model can predict the punching loads of the tests in an appropriate way. The primary objective of the simulations was to estimate the ultimate loads of the punching plates which are predicted well. The transition between the uncracked and the cracked

**FIGURE 10**  Force–deflection diagrams of the unstrengthened tests S01-P00, S01-P04, and the simulation N01-P00P04 (left) as well as for the strengthened plate S01-P01 and its simulation N01-P01 (right)

**FIGURE 11**  Comparison of the saw-cuts of the unstrengthened laboratory test S01-P04 and the strengthened test S01-P01 and their simulations
state takes place at a load higher than in the laboratory tests. The predicted shear crack patterns correspond to the cracks from the saw cuts. For the smallest of the three investigated reinforcement ratios the numerical model shows a development of the shear cracks different to the laboratory tests. The cracks are steeper which is due to the fact that these punching plates failed in laboratory close to a bending failure. Figure 14 illustrates that for the plates S03-P03 to S03-P06 the difference between simulation and laboratory test is higher than for the rest of the simulations. In particular for S03-P05 and S03-P06 the predicted loads are smaller than the tested ones. The comparison between simulation N02-P01 3R with S02-P01 shows that omitting the fourth row of screws has no negative effect on the strengthening system. This finding corresponds with the laboratory results.18

### 4 | CONCEPT OF A DESIGN APPROACH

#### 4.1 | Punching resistance of slabs strengthened with concrete screws

The developed design approach presented in this paper is kept close to the approach for the calculation of the punching resistance in EN 1992-1-1.30 This empirical design approach was chosen because it is currently still used in design practice and approval is also based on this approach. In Wörle37 and Spiegl,38 a design approach based on Model Code 201032 is presented, which is based less on empirical than on mechanical aspects.

In the presented approach the equations for the calculation of the design values of the maximum punching shear resistance along the control section $v_{Rd,max}$, the punching shear resistance of a slab without punching shear reinforcement along the control section $v_{Rd,c}$, and the punching shear resistance of a slab without punching shear reinforcement outside the control section $v_{Rd,c,out}$ remain unchanged according to the respective national specifications. Only the equation for the design value of the punching shear resistance of a slab with punching shear reinforcement along the control section $v_{Rd,cs}$ is modified. Figure 12 shows the steps to calculate the punching resistance according to EN 1992-1-1.

The following inequality condition has to be fulfilled to prove that the number of screws arranged in one row around the column is sufficient to take the acting force. The verification is performed along the basic control perimeter $u_1$, in a distance of twice the effective depth to the edge of the column.

$$\frac{\beta \cdot V_{Ed}}{u_1 \cdot d} \leq \left\{ \frac{v_{Rd,cs}}{k_{max} \cdot v_{Rd,c}} \right\}$$  \hspace{1cm} (3)

In Equation (3) $\beta$ describes the load eccentricity coefficient according to EN 1992-1-1, $V_{Ed}$ is the design value of the acting punching shear force and $u_1$ depicts the length of the basic control perimeter in a distance two times $d$ to the edge of the column with $d$ as the mean effective depth of the slab. The punching shear stress of the screw strengthened slab $v_{Rd,cs}$ is calculated according to Equation (4) while the punching shear stress of the plate

| Year | Test ID | Type of strengthening | Results |
|------|---------|-----------------------|---------|
|      |         |                       | $V_{test}$ (kN) | $V_{sim}$ (kN) | $\theta = \frac{V_{test}}{V_{sim}}$ |
| 2016 | S01-P00P04 | None                   | 699 | 724 | 1.04 |
|      | S01-P01 | 32 TSM-B22            | 858 | 887 | 1.03 |
|      | S01-P02 | 32 TSM-B22            | 843 | 843 | 1.00 |
|      | S01-P03 | 48 TSM-B22            | 986 | 1077 | 1.09 |
| 2017 | S02-P01 | 48 TSM-B22            | 899 | 916 | 1.02 |
|      | S02-P02 | 48 TSM-B22            | 984 | 992 | 1.01 |
|      | S02-P01 3R | 36 TSM-B22     | 899 | 894 | 1.00 |
| 2018 | S03-P01 | 24 TSM-B22            | 990 | 1038 | 1.05 |
|      | S03-P02 | 36 TSM-B22            | 1090 | 1078 | 0.99 |
|      | S03-P03 | 24 TSM-B22            | 896 | 878 | 0.98 |
|      | S03-P04 | 36 TSM-B22            | 950 | 1000 | 1.05 |
|      | S03-P05 | 24 TSM-B22            | 820 | 762 | 0.93 |
|      | S03-P06 | 36 TSM-B22            | 821 | 794 | 0.97 |
without shear reinforcement can be derived from Equation (7). The factor $k_{\text{max}}$ describes the effectiveness of the used punching reinforcement and the maximum punching resistance to be achieved with it.

The tests in Wörle\textsuperscript{23} and Walkner et al.\textsuperscript{18} showed that the punching resistance of a plate without shear reinforcement can be increased up to 40\% by the use of post-installed concrete screws driven up to the lower face of the flexural reinforcement. This increase amount equals to $k_{\text{max}} = 1.4$. If they are driven up to the upper face of the flexural reinforcement the increase of the resistance can be extended to 50\% which equals to $k_{\text{max}} = 1.5$. As it is very difficult to exclude the possibility of hitting the flexural reinforcement in the drilling process, especially for thick plates, a $k_{\text{max}}$-value of 1.4 is proposed to be used for the calculations.

The punching shear stress of the screw strengthened slab $v_{\text{Rd,cs}}$ is calculated according to the following equation:

$$v_{\text{Rd,cs}} = 0.75 \cdot v_{\text{Rd,c}} + 1.5 \cdot d \cdot A_{\text{sw}} \cdot f_{\text{yw,ef}} \cdot \frac{1}{u_1 \cdot d}. \quad (4)$$

In Equation (4), $v_{\text{Rd,c}}$ means the punching shear stress of the punching plate without shear reinforcement according to Equation (7), $s_r$ defines the radial distance between the screws, $A_{\text{sw}}$ describes the area of screw cross sections in one perimeter around the column according to Equation (5) and $f_{\text{yw,ef}}$ means the effective design strength of the screws from Equation (6).

$$A_{\text{sw}} = \min \left\{ \frac{A_{\text{sw,i}}}{A_{\text{sw,1.5d}}} \cdot \frac{d}{s_r}, \frac{d}{0.75d} \right\}. \quad (5)$$

In Equation (5) $A_{\text{sw,i}}$ defines the area of actually present screw cross sections in one perimeter around the column and $A_{\text{sw,1.5d}}$ describes the total area of screw cross sections in an distance ranging from 0.3 to 1.5 $d$ around the column. The cross section of one screw is calculated from its core diameter $\phi_w$ which is specified as 14.8 mm for the TSM-B16 screws and as 20.5 mm for the TSM-B22 screws.

$$f_{\text{yw,ef}} = 5.5 \cdot \frac{k_{\text{max}}}{\gamma_S} \cdot \frac{d}{\phi_w} \leq 0.5 f_{\text{yw}} \text{ in (N/mm$^2$)}. \quad (6)$$

The factor $\gamma_S$ in Equation (6) is the partial factor for the reinforcement steel according to EN 1992-1-1 (1.15 for the fundamental combination and 1.0 for accidental design situations). The design value of the yield strength of the reinforcement steel is described by $f_{\text{yw}}$ which can be presumed with 500 MPa/$\gamma_S$.

The punching shear stress of the punching plate without shear reinforcement according to EN 1992-1-1 is calculated with the following equation:

$$v_{\text{Rd,c}} = \max \left\{ \frac{C_{\text{Rd,c}} \cdot k \cdot (100 \cdot \rho l \cdot f_{\text{ck}})^{1/3} + k_1 \cdot \sigma_{\text{cp}}}{v_{\text{min}} + k_1 \cdot \sigma_{\text{cp}}} \right\}. \quad (7)$$

The calibration factor $C_{\text{Rd,c}}$ is defined as 0.18/$\gamma_C$ with $\gamma_C$ as partial factor for concrete according to EN 1992-1-1 (1.5 for the fundamental combination and 1.2 for accidental design situations). The scale factor $k$ can be derived from Equation (8). The mean flexural reinforcement ratio $\rho l$ is defined in Equation (9) and has to be calculated with $\rho_{l_x}$ and $\rho_{l_y}$ as the mean reinforcement ratio over the column in an area according to the column diameter enlarged by 3 $d$ on every side. $f_{\text{ck}}$ describes the characteristic value of the cylinder compression strength in N/mm$^2$, $k_1$ is a factor that accounts the effect of the normal concrete stresses acting in the plate ($k_1 = 0.1$) and $\sigma_{\text{cp}}$ defines those mean normal concrete stresses within the basic control perimeter (positive if compression). The minimum shear punching resistance $v_{\text{min}}$ is calculated with Equation (10).
The punching shear resistance with shear reinforcement. The characteristic value of the cylinder strength, the punching plate S02-P04 that failed at a too low number of load cycles (about 825,000 instead of 2 million) is excluded. The spread of 4 N/mm² between the mean value and the characteristic value of the compression strength is defined according to ÖNORM EN 206. The conversion factor between the cube compressive strength and the cylinder compressive strength is defined with 0.83 according to Staller.

To evaluate the reliability of the design approach the prognosis factor $\xi_k = V_{\text{test}, i} / V_{R,k,\text{calc}, i}$ is defined as a random parameter. According to ÖNORM EN 1990, section D.7, the level of safety is considered reasonable if the 5%-fractile value of the prognosis factor $\xi_{k,i}$ is equal or bigger than 1.0 on the characteristic level (partial factors $\gamma_C = \gamma_S = 1.0$). On design level (partial factors $\gamma_C = 1.5$ und $\gamma_S = 1.15$) the 0.1%-fractile value of the prognosis factor has to be one or bigger. The calculated punching resistances and prognosis factors are listed in Table 6.

According to Gulvanessian et al., the fractile coefficient $k_p$ has to be estimated for both cases according to EN 1990, table D.1, or table D.2 depending on the number of tests:

$$k_p = t_p \sqrt{\frac{1}{n+1}}.$$  

The factor $t_p$ equals the p-fractile of the $t$-distribution according to Student with $n - 1$ degrees of freedom. For a number of $n = 17$ tests the fractile factors for the 5%-fractile and the 0.1%-fractile yield:

$$k_{0.05} = t_{0.05} \sqrt{\frac{1}{n+1}} = -1.746 \sqrt{\frac{1}{17} + 1} = -1.796.$$  

$$k_{0.001} = t_{0.001} \sqrt{\frac{1}{n+1}} = -3.686 \sqrt{\frac{1}{17} + 1} = -3.793.$$  

For the distribution of the prognosis factor a log-normal distribution is assumed. For an evaluation on characteristic level the 5%-fractile value results in:

$$\xi_{k,i} = \ln \xi_{k,i}; \quad m_\xi = \frac{1}{n} \sum_{i=1}^{n} \xi_{k,i} = 0.170.$$  

$$s_\xi = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\xi_{k,i} - m_\xi)^2} = 0.054.$$  

### 4.2 Evaluation of the reliability of the design approach

The reliability of Equation (3) is evaluated on a basis of the four series of punching tests described in Wörle and Walkner et al. The unstrengthened plates are not included in the sample. However, the cyclically loaded punching plate S02-P04 that failed at a too low number of load cycles (about 825,000 instead of 2 million) is excluded.

Table 5 defines the input values for the calculation of the punching resistances with shear reinforcement. The characteristic value of the cylinder strength $f_{ck}$ is derived from the measured compression strenghts of cylinders and cubes by:

$$f_{ck} = \begin{cases} f_{cm, cyl} - 4 \text{ N/mm}^2, \\ 0.83 f_{cm, cube} - 4 \text{ N/mm}^2. \end{cases}$$  

Inequality (11) has to be fulfilled to prove that the strengthened area has sufficient size and that there are enough screws. The verification is performed along the control perimeter $u_{out}$ at which shear reinforcement is not required. $u_{out}$ has to be placed at a distance not greater than 1.5 $d$ to the outermost row of screws. Therefore, at the perimeter $u_{out}$ the following inequation has to be fulfilled:

$$\frac{\beta \cdot V_{Ed}}{u_{out} \cdot d} \leq v_{R,d,c, out}.$$  

According to EN 1992-1-1 the punching shear resistance outside the shear reinforced area $v_{R,d,c, out}$ is equal to the punching shear resistance $v_{R,d,c}$ of a plate without punching shear reinforcement.

The rules for the arrangement of punching shear reinforcement around the column are adopted from EN 1992-1-1 as shown in Figure 12. In addition, minimum distances between the screws were defined:

TSM-B16: $s_{min} \geq \min \begin{cases} d/2, \\ 10 \text{ cm} \end{cases}$

TSM-B22: $s_{min} \geq \min \begin{cases} d/2, \\ 15 \text{ cm} \end{cases}$.  

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \text{ with } d \text{ in (mm).} \quad (8)$$  

$$\rho_l = \sqrt{\frac{\rho_{ck}}{\rho_y}} \leq 0.02. \quad (9)$$  

$$v_{\text{min}} = 0.035 \cdot \sqrt{k^3 \cdot f_{ck}}. \quad (10)$$  

$$f_{ck} = \begin{cases} f_{cm, cyl} - 4 \text{ N/mm}^2, \\ 0.83 f_{cm, cube} - 4 \text{ N/mm}^2. \end{cases}$$  

The spread of 4 N/mm² between the mean value and the characteristic value of the compression strength is defined according to ÖNORM EN 206. The conversion factor between the cube compressive strength and the cylinder compressive strength is defined with 0.83 according to Staller.
### Table 5  
Input variables to calculate the punching shear resistance

| Year | Test ID | d (cm) | u1 (cm) | ρl (%) | fc (MPa) | ϕw (mm) | A_{sw,1,5d} (cm²) | A_{sw} (cm²) | k_{max} |
|------|---------|--------|---------|--------|----------|---------|--------------------|--------------|---------|
| 2011 | P02     | 15.5   | 289.0   | 2.00   | 35.3     | 14.8    | 41.29              | 13.76        | 1.50    |
|      | P03     | 15.5   | 289.0   | 2.00   | 36.7     | 14.8    | 41.29              | 13.76        | 1.20    |
|      | P04     | 15.4   | 287.8   | 2.00   | 33.7     | 20.5    | 79.22              | 26.41        | 1.50    |
| 2016 | S01-P01 | 16.0   | 279.6   | 1.40   | 29.8     | 20.5    | 52.81              | 22.00        | 1.50    |
|      | S01-P02 | 16.4   | 284.6   | 1.36   | 28.9     | 20.5    | 52.81              | 21.47        | 1.40    |
|      | S01-P03 | 16.1   | 280.9   | 1.39   | 30.0     | 20.5    | 79.22              | 32.80        | 1.50    |
| 2017 | S02-P01 | 16.1   | 280.9   | 1.39   | 23.7     | 20.5    | 79.22              | 32.80        | 1.40    |
|      | S02-P02 | 16.1   | 280.9   | 1.39   | 23.5     | 20.5    | 79.22              | 32.80        | 1.50    |
|      | S02-P03 | 16.1   | 280.9   | 1.39   | 23.2     | 14.8    | 41.29              | 17.10        | 1.40    |
|      | S02-P05 | 16.1   | 280.9   | 1.39   | 24.7     | 20.5    | 79.22              | 32.80        | 1.40    |
|      | S02-P06 | 16.2   | 282.1   | 1.38   | 24.5     | 20.5    | 79.22              | 32.80        | 1.40    |
| 2018 | S03-P01 | 16.1   | 280.9   | 1.39   | 37.1     | 20.5    | 52.81              | 21.87        | 1.40    |
|      | S03-P02 | 16.1   | 280.9   | 1.39   | 36.2     | 20.5    | 79.22              | 32.80        | 1.40    |
|      | S03-P03 | 16.2   | 282.1   | 1.06   | 36.6     | 20.5    | 52.81              | 21.73        | 1.40    |
|      | S03-P04 | 16.2   | 282.1   | 1.06   | 37.0     | 20.5    | 79.22              | 32.60        | 1.40    |
|      | S03-P05 | 16.2   | 282.1   | 0.78   | 38.3     | 20.5    | 52.81              | 21.73        | 1.40    |
|      | S03-P06 | 16.1   | 280.9   | 0.78   | 37.9     | 20.5    | 79.22              | 32.80        | 1.40    |

### Table 6  
Calculated punching shear resistances and prognostic factors ξk or ξd

| Year | Test ID | V_{test} (kN) | V_{Rk.c} (kN) | k_{max} \cdot V_{Rk.c} (kN) | V_{Rk.cs} (kN) | ξk | k_{max} \cdot V_{Rd.c} (kN) | V_{Rd.cs} (kN) | ξd |
|------|---------|---------------|---------------|-----------------------------|----------------|----|-----------------------------|----------------|----|
| 2011 | P02     | 906           | 667           | 1000                        | 780            | 1.161 | 444                         | 580            | 1.561 |
|      | P03     | 793           | 675           | 811                         | 731            | 1.085 | 450                         | 535            | 1.482 |
|      | P04     | 937           | 650           | 974                         | 870            | 1.077 | 433                         | 650            | 1.443 |
| 2016 | S01-P01 | 858           | 558           | 838                         | 759            | 1.131 | 372                         | 558            | 1.536 |
|      | S01-P02 | 843           | 572           | 801                         | 754            | 1.118 | 381                         | 534            | 1.579 |
|      | S01-P03 | 986           | 564           | 847                         | 937            | 1.165 | 376                         | 564            | 1.747 |
| 2017 | S02-P01 | 899           | 522           | 730                         | 870            | 1.231 | 348                         | 487            | 1.846 |
|      | S02-P02 | 984           | 520           | 780                         | 903            | 1.262 | 347                         | 520            | 1.893 |
|      | S02-P03 | 860           | 518           | 726                         | 735            | 1.185 | 346                         | 484            | 1.778 |
|      | S02-P05 | 908           | 529           | 741                         | 876            | 1.226 | 353                         | 494            | 1.838 |
|      | S02-P06 | 903           | 532           | 745                         | 881            | 1.213 | 355                         | 496            | 1.819 |
| 2018 | S03-P01 | 990           | 606           | 848                         | 774            | 1.279 | 404                         | 566            | 1.750 |
|      | S03-P02 | 1009          | 601           | 841                         | 930            | 1.296 | 400                         | 561            | 1.944 |
|      | S03-P03 | 896           | 557           | 779                         | 739            | 1.213 | 371                         | 519            | 1.725 |
|      | S03-P04 | 950           | 559           | 782                         | 901            | 1.215 | 372                         | 521            | 1.822 |
|      | S03-P05 | 820           | 510           | 714                         | 704            | 1.165 | 340                         | 476            | 1.723 |
|      | S03-P06 | 821           | 503           | 705                         | 857            | 1.165 | 336                         | 470            | 1.747 |

Note: The bold numbers mark the decisive punching shear resistance from the calculation.
\[ \xi_{k,0.05} = e^{m_c + k_{0.05} \cdot \xi} = e^{0.170 - 1.796 \cdot 0.054} = 1.077 \] (19)

\[ \Rightarrow \text{reaches the target value of 1.0} \]

For an evaluation on design level the 0.1%-fractile value results in:

\[ \xi_{d,0.001} = e^{m_c + k_{0.001} \cdot \xi} = e^{0.539 - 3.793 \cdot 0.088} = 1.227. \] (22)

\[ \Rightarrow \text{reaches the target value of 1.0} \]

\[ s_c = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\xi_{d,i} - m_c)^2} = 0.088 \] (21)

For both, the characteristical level and the design level, the fractile values exceed the necessary target value of 1.0.
According to Figure 13 the major factors of influence are described without a trend (Figure 13a–d—tests of series 2018 highlighted in orange). Therefore, the design approach for calculating the punching resistance of screw strengthened plates can be classified as sufficiently secure for the tested parameters. Figure 13e shows the density function and the distribution function for the evaluation on characteristic level and Figure 13f shows them for the design level. The slender density function demonstrates the accurate forecasting. Due to the partial factors the spread increases for the evaluation on design level whereby the 0.1%-fractile value exceeds the target value of 1.0 considerably.

5 | COMPARISON OF THE RESULTS FROM NUMERICS AND DESIGN APPROACH

Figure 14 shows a comparison between the test results, the simulations, and the punching resistances derived from the design approach. The correlation between the punching loads from the design approach and the laboratory tests as well as for the simulated punching loads and the test results is shown in Figure 15. It shows that the simulations and the test results correlate accurate and the loads calculated with the design approach are sufficiently secure.

**FIGURE 14** Comparison of the results of the design approach, the simulations and the laboratory tests

**FIGURE 15** Scattering of the recalculation of the experiments
**TABLE 7**  Parameters and results for additionally performed simulations

| Test ID | $R_s$ (cm) | $R_q$ (cm) | $b_c$ (cm) | $h$ (cm) | $d$ (cm) | $\phi$ (mm) | $s$ (cm) | $\phi_w$ (mm) | $s_0$ (cm) | $s_e$ (cm) | $n_e$ | $n_u$ |
|---------|------------|------------|------------|----------|----------|--------------|---------|--------------|----------|----------|-------|-------|
| NZ-P01  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 16           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 8     |
| NZ-P02  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 16           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 12    |
| NZ-P03  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 14           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 8     |
| NZ-P04  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 14           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 12    |
| NZ-P05  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 16           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 8     |
| NZ-P06  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 16           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 12    |
| NZ-P07  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 14           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 8     |
| NZ-P08  | 135.0      | 120.0      | 25.0       | 20.0     | 16.4     | 14           | 9.0     | 20.2         | 6.0      | 10.0     | 3     | 12    |
| NZ-P09  | 202.5      | 180.0      | 37.5       | 30.0     | 24.6     | 24           | 13.5    | 20.2         | 9.0      | 15.0     | 4     | 12    |
| NZ-P10  | 337.5      | 300.0      | 62.5       | 50.0     | 41.0     | 40           | 22.5    | 20.2         | 15.0     | 25.0     | 4     | 12    |

**FIGURE 16**  Comparison between the results of the design approach and the simulations for additional parameter variations
6 | FURTHER INVESTIGATIONS AND SIMULATIONS

Since the punching shear resistances of the tests could be predicted well by the numerical model, other parameters were varied and compared with the results of the design approach. The main parameters of the plates investigated in this study, can be found in Table 7. In contrast to the slabs tested in the laboratory, concrete of strength class C25/30 was selected for the simulations NZ-P01 to NZ-P04. Two of these four slabs had a flexural reinforcement ratio of 1.36% and 1.04%, respectively. Two different shear reinforcement ratios were selected for each of these two different flexural reinforcement ratios. The shear reinforcement ratio \( \rho_w \) is defined according to the following equation:

\[
\rho_w = \frac{A_{sw,1.5\,d}}{1.5\,d\cdot(b_c + 1.5\,d)\cdot\pi}. \tag{23}
\]

These four simulations were repeated with concrete of strength class C50/60 (NZ-P05 to NZ-P08).

For the NZ-P09 and NZ-P10 simulations, the slab thickness was chosen to be 30 and 50 cm, respectively, and the dimensions of the slab were adjusted accordingly. The number of bolts was also increased in these tests. Nevertheless, the shear reinforcement ratio decreased significantly, since the bolt diameter was still assumed to be 20.2 mm.

The evaluation in Figure 16 shows that the design approach provides a reliable prognosis even for these boundary conditions, although the safeties are significantly higher for the simulations with high concrete strength.

With the help of the numerical model, further investigations could be made. For example, it would be interesting to simulate how a gradual increase in the number of concrete screws or an inclined installation of the screws would affect the punching shear resistance.

7 | CONCLUSIONS

In this article, a numerical model created with the program ATENA was presented. It is able to predict the punching loads of unstrengthened and screw strengthened punching plates. The screws were modeled as truss elements with bond-slip relationship. The punching loads from the laboratory tests could be predicted very well. To achieve representative results while keeping the necessary computation time short some minor simplifications in the description of the behavior of the screws were met. The following advantages and disadvantages of the model can be pointed out:

- The transition between the uncracked and the cracked state takes place at a load higher than in the laboratory tests. To describe the behavior of the plate in a better way the tensile strength and the fracture energy were adjusted. The stiffness is still overestimated while the deformation is underestimated. This is acceptable as the primary objective of the simulations was to estimate the ultimate loads of the punching plates which are predicted well.
- The comparison between the simulated shear cracks and the documented cracks from the saw cuts show that the shear cracks are predicted in an appropriate way.
- The bond-behavior of the screws was modeled according to pull-out tests performed on two types of concrete. The results could be improved by performing additional pull-out tests with different concrete strengths and in cracked concrete.
- For the modeling of the screws it was assumed that only the self-cutting thread is bonded to the concrete and that there is no bond along the shaft. This conservative assumption is appropriate for thin plates. This assumption simplifies the modeling and the calculation and provides safe results.
- For low degrees of flexural reinforcement the model predicts bending failure instead of punching failure. This is due to the fact that the two tests with low flexural reinforcement degrees were close to bending failure in laboratory too.

In the second part of the article a design approach based on the punching calculations from EN 1992-1-1 is presented. The approach allows it to take the positive influence of strengthening screws on the punching resistance into account. The evaluation of the design approach showed that it predicts the punching loads with sufficient security. The comparison between the punching loads from the numerical model and the design approach as well as the laboratory tests showed that the numerical model and the design approach predict the punching loads very well. The design approach was included into the technical assessment for the concrete screws of the system reLAST as post-installed punching reinforcement system [Z-15.1-340 (2019)].

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOTATION

\( A_{sw} \) area of screw cross sections in one perimeter around the column

\( A_{sw,i} \) area of actually present screw cross sections in one perimeter around the column

\( A_{sw,1.5d} \) total area of screws cross sections in a distance from 0.3 \( d \) bis 1.5 \( d \) around the column

\( b_c \) diameter of the column stub

\( C_{Rd,c} \) calibration factor

\( d \) measured mean value of the effective depth in both directions of the flexural reinforcement

\( f_c \) cylinder compressive strength at time of slab testing

\( f_{ck} \) characteristic value of the cylinder compressive strength

\( f_{cm,cyl} \) mean value of the cylinder compressive strength

\( f_{cm,cube} \) mean value of the cube compressive strength

\( f_{ct} \) tensile strength of the concrete

\( f_{ct,sim} \) tensile strength of the concrete used for the simulation

\( f_{ywd} \) design yield strength of concrete screws

\( f_{ywd,ef} \) effective design yield strength of concrete screws

\( G_f \) fracture energy

\( G_{f,sim} \) fracture energy used for the simulation

\( h \) slab thickness

\( k \) scale factor

\( k_{max} \) effectiveness coefficient for the used punching reinforcement

\( k_p \) fractile coefficient

\( k_1 \) factor to account the effect of the normal concrete stresses acting in the plate

\( n \) number of tests

\( n_r \) number of rows of the strengthening elements around the column

\( R_a \) radius of the punching plate

\( R_q \) radius of the load introduction

\( s \) spacing of the flexural reinforcement in both directions

\( s_0 \) radial distance between the column edge and the first row of screws

\( s_r \) radial distance between the strengthening elements

\( s_{\min} \) minimum distance between the strengthening elements

\( t_p \) \( p \)-fractile of the t-distribution

\( u_1 \) length of the basic control perimeter

\( u_{out} \) control perimeter at which shear reinforcement is not required

\( V_{Ed} \) design value of the acting punching shear force

\( V_{\text{mean}} \) mean value of the punching capacity of the slab

\( v_{\min} \) minimum shearing punching resistance

\( v_{Rd,c} \) punching shear resistance of a slab without punching shear reinforcement

\( v_{Rd,cs} \) punching shear resistance of a slab with punching shear reinforcement

\( v_{Rd,c,out} \) punching shear resistance without punching shear reinforcement outside control section

\( V_{sim} \) maximum punching shear resistance

\( V_{\text{test}} \) punching capacity derived from the laboratory test

\( V_{R,\text{calc}} \) punching capacity derived from the design approach

\( \beta \) load eccentricity coefficient

\( \gamma_s \) partial factor for the reinforcement steel

\( \gamma_c \) partial factor for the concrete

\( \Theta \) model uncertainty

\( \phi \) bar diameter of the flexural reinforcement

\( \phi_w \) core diameter of the screw

\( \rho_1 \) mean value of the flexural reinforcement ratio of the tensile bars

\( \rho_{ls} \) flexural reinforcement ratio of the tensile bars in x-direction

\( \rho_{ly} \) flexural reinforcement ratio of the tensile bars in y-direction

\( \rho_w \) shear reinforcement ratio

\( \sigma_{cp} \) mean normal concrete stresses within the basic control perimeter

\( \tau_{max} \) bond-strength

\( \xi \) random parameter

\( \zeta \) random parameter

\( s_{\xi} \) estimated standard deviation

\( m_{\xi} \) mean value of the random parameters distribution

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