Concrete screws as a post-installed punching shear reinforcement

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Abstract
The strengthening of concrete structures is becoming more and more important. To achieve this need for strengthening measures, technically innovative, simple and economical systems for subsequent strengthening are required. At the University of Innsbruck, a system for subsequent strengthening of the punching shear zone through the installation of concrete screws has been developed. These screws are installed from the soffit side of the slab in vertically predrilled holes and are arranged concentrically around the support. This paper discusses the results of four test series, with a total of 21 specimens used to develop the system. The system, which can be very easily installed, demonstrates a significant increase of the shear punching capacity and a reduction in brittle failure modes. In addition, cyclic loading with typical levels of service load has no negative effect on the effectiveness of the system. Finally, the influence of the flexural reinforcement ratio on the effectiveness of the strengthening system was investigated.

KEYWORDS
concrete screws, strengthening, punching shear reinforcement

1 | INTRODUCTION

Due to the total resource of built structures and their age, the strengthening and restoration of existing structures is gaining in importance as a subdomain of civil engineering. For structures made of reinforced concrete, the punching shear resistance is of particular importance. Inspections and recalculations of existing bridges and slabs have revealed that their support areas often show a lack of punching shear resistance. The main reasons for such structural deficits are: the age of infrastructure buildings,1,2 more restrictive design rules due to the harmonization of the European standards and codes3,4 and increased traffic loads.5 Finally, poor maintenance can also lead to a decrease in load carrying capacity.

As demolishing and rebuilding of existing structures is expensive, developing a methodology for subsequent strengthening of these structures should be the aim. A description and a comparison of different strengthening concepts to increase the punching shear resistance and deformability can be found in Stibernitz.6 Examples of such approaches include: methods which focus on enlarging the supporting area,7 applying additional external...
reinforcement in the form of carbon fiber reinforced polymer (CFRP) strips\textsuperscript{8-10} applying an additional concrete layer in combination with additional shear reinforcement,\textsuperscript{11} using prestressed carbon CFRP straps,\textsuperscript{12} applying an additional layer of textile-reinforced mortar,\textsuperscript{13} introduce prestressed vertical bolts\textsuperscript{14} or using post-installed bars in inclined holes and bonded by a high-performance epoxy adhesive.\textsuperscript{15}

It should be noted that the majority of the current methods are not optimal as they require a high installation effort with high costs and require access to the upper surface of the structure. A new method for subsequent strengthening of structures aims to avoid these disadvantages. The basic principle of this strengthening method is to install concrete screws into the slab around the supporting column (see Figure 1 left, References 16 and 17). The screws can transfer forces between the tensile and the compressive zone of the slab and thus significantly increase the punching shear resistance in a simple, cost and resource effective manner.

Concrete screws are fastening elements made of steel with a self-tapping thread at their front end (Figure 1 right). The screws are installed in predrilled holes, whereby the drill hole diameter is defined by the screw manufacturer and is slightly smaller than the diameter of the concrete cutting thread. During the installation, the threads cut into the sidewalls of the drill holes and thus form a mechanical interlock with the surrounding concrete. Before screwing in the screws, the drill holes must be cleaned with brushes and compressed air. A composite mortar is usually inserted, after cleaning the borehole of drill dust, to close the gap between the sidewall and the screw and to support the mechanical interlock of the thread by material bond. For a fast installation, the screws can be installed using an impact screwdriver. Finally, a pressure distribution disk and a Nord-Lock wedge lock washer are arranged on the airside and a screw nut is tightened with a defined torque moment. The Nord-Lock element prevents the nut from loosening under dynamic loads and can compensate a slight misalignment between the screw and the anchor base.

To increase the punching resistance, the screws are arranged concentrically around the column in several rings and they act in a similar way as a conventional punching shear reinforcement. As the shear cracks develop under rising load, the screws transfer the resulting forces across the cracks. The described strengthening system is characterized by a very fast and easy installation that can be performed from one side of the structure only. Therefore, the opposite side remains untouched. As a result, there is no restriction of the use of the construction during installation. For example, traffic on bridges does not need to be restricted. Further, road surfaces, ballast beds and sealings remain untouched. In Reference 18, it was shown that the very same system can be used for concrete beams to increase their shear capacity.

2 | LABORATORY TESTS

To investigate the effectiveness of the new strengthening system and to verify its suitability for the strengthening of flat slabs and bridges, four test series were carried out at the University of Innsbruck. The first series was tested in 2011 and consisted of four specimens. The test results showed that compared to an un-strengthened slab the

\textbf{FIGURE 1} Principle for punching shear reinforcement with post-installed concrete screws (left and center) and concrete screw with anchoring (right)—(adhesive agent in yellow)
punching shear resistance can be increased more than 50% by using subsequently installed concrete screws. This first series of experiments was presented in References 16 and 17 and will not be discussed in more detail here. The second series was tested in 2016 and consisted of five specimens.\textsuperscript{19} Two of the specimens were tested without punching shear reinforcement. For the remaining three specimens, the number of concrete screws and the installation depth were varied. In 2017 the third series with six specimens was tested. All specimens in this series were strengthened with concrete screws and three specimens were subjected to cyclical loading.\textsuperscript{20} The fourth and provisionally last test series was carried out in 2018. In this test series, the degree of flexural reinforcement and the number of concrete screws were varied.\textsuperscript{21}

2.1 Test setup

The punching shear tests were performed on circular slabs with a diameter of 2,700 mm and a slab thickness of 200 mm (see Figure 2). All specimens had circular
Column stubs, which were poured simultaneously with the slabs. The column stubs had a diameter of 250 mm and a height of 100 mm. The punching shear load was applied by a centrically arranged hydraulic jack. The pressure force of the hydraulic jack was anchored back into a massive counter slab via 12 tensile bars (ø26.5 mm) arranged 1,200 mm from the centre of the tested slabs. The test setup corresponds approximately to the supporting torque range of a flat ceiling system with a span of $l = 5.45$ m ($= 1.2$ m/0.22) (the value 0.22 can be found in Reference 22. With an effective depth of 16.4 cm, this results in a ceiling slenderness of about $l/d = 33$ ($=5.45/0.164$).

In the 2016 and 2017 tests, a hydraulic jack with a nominal load of 1.0 MN was used. This jack was able to apply a cyclical load with high frequency. In the 2018

| Year | Test ID  | $b_s$ (mm) | $b_q$ (mm) | $h$ (mm) | $b_c$ (mm) | $d_{nom}$ (mm) | $d$ (mm) | $d_c$ (mm) | $d_y$ (mm) | Shear reinforcement |
|------|----------|------------|------------|----------|------------|----------------|---------|-----------|-----------|-------------------|
| 2016 | S01-P00  | 2,700      | 2,400      | 200      | 250        | 164           | 161     | 169       | 153       |                   |
|      | S01-P01  |            |            |          |            |                |         |           |           |                   |
|      | S01-P02  |            |            |          |            |                |         |           |           |                   |
|      | S01-P03  |            |            |          |            |                |         |           |           |                   |
|      | S01-P04  |            |            |          |            |                |         |           |           |                   |
| 2017 | S02-P01  | 2,700      | 2,400      | 200      | 250        | 164           | 161     | 169       | 153       |                   |
|      | S02-P02  |            |            |          |            |                |         |           |           |                   |
|      | S02-P03  |            |            |          |            |                |         |           |           |                   |
|      | S02-P04  |            |            |          |            |                |         |           |           |                   |
|      | S02-P05  |            |            |          |            |                |         |           |           |                   |
|      | S02-P06  |            |            |          |            |                |         |           |           |                   |
| 2018 | S03-P01  | 2,700      | 2,400      | 200      | 250        | 164           | 161     | 169       | 153       |                   |
|      | S03-P02  |            |            |          |            |                |         |           |           |                   |
|      | S03-P03  |            |            |          |            |                |         |           |           |                   |
|      | S03-P04  |            |            |          |            |                |         |           |           |                   |
|      | S03-P05  |            |            |          |            |                |         |           |           |                   |
|      | S03-P06  |            |            |          |            |                |         |           |           |                   |

*Friction-welded.
2.2 | Reinforcement and experimental programme

All specimens in series 2016, 2017 and two specimens in series 2018 (S03-P01 and S03-P02) had the same flexural reinforcement (Figure 3). The flexural tension reinforcement of these slabs consisted of end-hooked deformed steel bars with a diameter of 16 mm. The bar distance was equal to 90 mm in both directions. The nominal value of the concrete cover was 20 mm. This leads to an averaged effective depth of 164 mm and a flexural reinforcement ratio of 1.37%. The configuration of specimens S03-P03 and S03-P04 maintained the same bar spacing and effective depth, but the bar diameter was reduced from 16 to...
For the final two specimens S03-P05 and S03-P06 the bar diameter was further reduced to 12 mm. Thus, in series 2018 the nominal values of the flexural reinforcement ratio were 1.37, 1.04, and 0.77%. All specimens were reinforced at their lower sides with straight bars with a diameter of 8 mm at 90 mm in both X and Y directions. This reinforcement has a negligible influence on the punching shear resistance and only serves to absorb the tensile stresses when lifting the slabs with the indoor crane. In order to avoid shear failure along the edge support, additional hooks were arranged in the area near the edge. The actual location of the flexural reinforcement was determined before pouring the concrete and verified after testing with measurement on saw cuts through the specimens. There were slight deviations from the nominal values of not more than 4 mm. The measured values of the effective depth and the resulting flexural reinforcement ratios can be found in Table 1. This table summarizes the main geometrical parameters of the specimens.

Figure 4 shows the geometrical dimensions of two different types of concrete screws used in this work (system reLAST© from TOGE Dübel GmbH & Co. KG). The screw denotation can be understood as follows: the number after the letter B is the borehole diameter in mm, the number after the letter M is the diameter of the ISO-thread and the last number describes the length of the concrete screws in mm. The screws used were produced in two ways: by friction welding and single piece screws. The friction-welded screws are marked with *. The advantage of friction-welded screws is that they are available in longer lengths than single piece screws. All screws were installed in combination with adhesive bond. The used adhesive agent was CF-T300V from ChemoFast.

The geometrical arrangements of the screws are shown in Figures 5–7. The first row of screws was positioned at a distance of 60 mm (=0.37 \( d_{\text{nom}} \)) from the edge of the column stub. The distance between each screw row was 100 mm (=0.61 \( d_{\text{nom}} \)).

Figure 5 shows the arrangement of the screws for the five specimens used in series 2016. The aim was to investigate the influence of the installation depth and the number of screws on the performance of the strengthening system. Specimens S01-P00 and S01-P04 were not strengthened and thus served as reference tests to determine the punching strength of slabs without shear reinforcement. The three strengthened specimens were

![Figure 6](image-url)
equipped with TSM-B22 screws. Specimen S01-P01 was strengthened with 32 screws (4 rows with 8 screws per row) installed to a depth of 180 mm, up to the upper face of the flexural reinforcement. Specimen S01-P02 featured the same screw configuration as S01-P01 but the screws were only installed up to the lower face of the flexural reinforcement (installation depth 148 mm). Specimen S01-P03 was strengthened with an increase in the number of screws from 32 to 48 (4 rows with 12 screws per row).

Figure 6 shows the arrangement of the screws for the six specimens used in series 2017. The aim was to investigate the influence of cyclic loading on the effectiveness of the strengthening system and with the final specimen, to determine the influence of omitting the outermost (fourth) strengthening row. All six specimens were strengthened with 12 screws per row. Specimen S02-P01 was strengthened with 48 screws (4 rows) with an installation depth of 148 mm, up to the lower side of the flexural reinforcement. This test served as a reference test in this series. For specimen S02-P02, the installation depth was increased to 180 mm from 148 mm, whereby the screws reached the upper side of the flexural reinforcement. For specimen S02-P03, thinner screws with a borehole diameter of 16 mm were used. A cyclic loading with a target value of 2 million load cycles was applied to specimens S02-P04 to S02-P06. In the test of S02-P04, the cyclic load level was cycled between 1/3 and 2/3 of the failure load of the reference test S02-P01. In the tests of S02-P05 and S02-P06 the cyclic load level was cycled between 30 and 50% of the failure load of S02-P01. Specimens S02-P04 and S02-P05 had the same geometry and screw reinforcement as specimen S02-P01. The test of S02-P06 was carried out identically to the test of S02-P05, with the exception that the fourth outermost row of screws was omitted.

Figure 7 shows the arrangement of the screws for the six specimens used in series 2018. The aim was to investigate the influences of the flexural reinforcement ratio and the shear reinforcement ratio on the efficiency of the strengthening system. All six specimens were strengthened with concrete screws of type TSM-B22. The screws were installed on three rows and were screwed to the lower side of the flexural reinforcement. The flexural reinforcement ratios were 1.39, 1.06, and 0.78%. For each flexural reinforcement ratio, two specimens with different ratios of...
shear reinforcement were tested, one specimen was strengthened with 8 screws per row (24 screws) and the other one with 12 screws per row (36 screws).

### 2.3 Material properties

Table 2 shows the material properties of the concrete used, the flexural reinforcement bars and the screws. To ensure comparability, all specimens of one series were poured simultaneously with concrete from the same batch. The maximum aggregate size for all specimens was 16 mm. The steel used for reinforcement had a quality of B550B. The steel properties of the screws in Table 2 indicate that the friction-welded screws do not have the same level of properties as the screws made from a single piece. Nevertheless, the failure of the connection between the screws and the surrounding concrete is dominated by

| Year | Test ID | Age at testing (d) | $f_{c,\text{cube},28}$ (MPa) | $f_{c,\text{cube}}$ (MPa) | $f_c$ (MPa) | $f_{ct,\text{sp}}$ (MPa) | $E_c$ (GPa) |
|------|---------|-------------------|-----------------|-----------------|---------|-----------------|-----------|
| 2016 | S01-P00 | 70                | 40.6            | 40.7            | 32.2    | 3.7             | -         |
|      | S01-P01 | 72                | 40.7            | -               | -       | -               | -         |
|      | S01-P02 | 77                | 40.8            | 32.9            | 3.0     | 28.1            | -         |
|      | S01-P03 | 79                | 40.9            | -               | -       | -               | -         |
|      | S01-P04 | 84                | 41.8            | 34.6            | 3.0     | -               | -         |
| 2017 | S02-P01 | 118               | 26.7            | 34.1            | 27.7    | 2.7             | -         |
|      | S02-P02 | 138               | 33.0            | -               | -       | -               | -         |
|      | S02-P03 | 141               | 32.7            | -               | -       | 25.9            | -         |
|      | S02-P04 | 176               | 34.3            | 28.6            | 2.8     | -               | -         |
|      | S02-P05 | 219               | 34.6            | -               | -       | -               | -         |
|      | S02-P06 | 251               | 33.8            | 28.5            | 2.3     | -               | -         |
| 2018 | S03-P01 | 65                | 42.7            | 48.5            | 41.1    | -               | -         |
|      | S03-P02 | 70                | 50.1            | 40.2            | -       | -               | -         |
|      | S03-P03 | 72                | 49.6            | 40.6            | -       | -               | -         |
|      | S03-P04 | 76                | 51.2            | 41.0            | -       | 33.6            | -         |
|      | S03-P05 | 79                | 49.5            | 42.3            | -       | -               | -         |
|      | S03-P06 | 83                | 50.7            | 41.9            | 3.7     | -               | -         |

| Year | Test ID | $f_y$ (MPa) | $f_t$ (MPa) | $E_s$ (GPa) | $f_{yw}$ (MPa) | $f_{tw}$ (MPa) | $E_{sw}$ (GPa) |
|------|---------|-----------|-----------|-----------|---------------|---------------|--------------|
| 2016 | S01-P00 | 513       | 650       | 199       | -             | -             | -            |
|      | S01-P01 | 598       | 749       | 210       |               |               | -            |
|      | S01-P02 | 812       | 856       | 206       |               |               | -            |
|      | S01-P03 | 598       | 749       | 210       |               |               | -            |
|      | S01-P04 | -         | -         | -         | -             | -             | -            |
| 2017 | S02-P01 | 610       | 663       | 205       | 597           | 746           | 175          |
|      | S02-P02 | -         | -         | -         | -             | -             | -            |
|      | S02-P03 | -         | -         | -         | 481           | 548           | 197          |
|      | S02-P04 | -         | -         | -         | 597           | 746           | 175          |
|      | S02-P05 | -         | -         | -         | -             | -             | -            |
|      | S02-P06 | -         | -         | -         | 598           | 749           | 210          |
| 2018 | S03-P01 | 577       | 680       | 207       | 563           | 712           | 185          |
|      | S03-P02 | -         | -         | -         | -             | -             | -            |
|      | S03-P03 | -         | -         | -         | 570           | 673           | 207          |
|      | S03-P04 | -         | -         | -         | -             | -             | -            |
|      | S03-P05 | -         | -         | -         | 640           | 684           | 207          |
|      | S03-P06 | -         | -         | -         | -             | -             | -            |
the concrete strength. Therefore, the screws will never reach their yielding point and the difference between the screw types properties is of no significant relevance.

2.4 | Test procedure and measurement

The static tests were loaded using an automatic displacement controller applying a velocity of 0.6 mm/min. At two defined loads (208 and 383 kN) the displacements were kept constant to record the crack patterns on the top surface. After a decrease of load to a level of about 100–150 kN, the test specimens were loaded up to failure. For the cyclic loading tests (S02-P04, S02-P05 and S02-P06), first the load was applied identically to the static tests, but before loading up to failure, a cyclic loading with a target value of 2 million load cycles was applied. For the first cyclic test on specimen S02-P04, the maximum and minimum load were set at 33 and 66% of the failure load from the static reference test (S02-P01). This cyclic load level was chosen intentionally high to study the behavior of the system under loads above the fatigue load level. As test S02-P04 did not achieve 2 million load cycles and failed after 824,967 load cycles, the maximum and minimum load for S02-P05 and S02-P06 were adapted to realistic load levels in consideration of real bridge geometry and fatigue load according to the specifications of EN 1991-2. Thus, the maximum and minimum load were set to 50% and 30% of the load in the ultimate limit state (ULS) which was defined as the ultimate load of the static reference test S02-P01.

The arrangement of the measuring system is shown in Figure 8. The measurements include the tension forces of the 12 threadbars with integrated load cells (LC 01 to LC 12), the load and displacement of the hydraulic jack, vertical deformation measurements of the top surface of the slab (U1 to U9), strain measurements of the flexural reinforcement (SG x and SG y), strain measurements in radial and tangential direction on the bottom surface of the slab close to the column stub (SG_radial and SG_tangential) as well as strain measurements of eight respectively six concrete screws for each specimen (R1S1 to R4S2).

FIGURE 8 Arrangement of the measuring system

2.5 | Installation time

An evaluation of the installation time of this strengthening system was carried out during the testing of series 2018. A specimen with 24 screws installed to the lower side of the flexural reinforcement at a dept. of 148 mm was used for this study. The processes included in this assessment were: the drilling and the cleaning of the boreholes, the insertion of the adhesive agent and the installation of the screws including the cropping of the shafts and the fastening of the nuts. The 24 boreholes were drilled twice to a depth of 150 mm, first with a diameter of 16 mm and in a second step, they were widened to a diameter of 22 mm. These two steps of the procedure took 50 min. It took another 32 min to clean the holes, insert the bonding agent, install the screws, crop the shafts and fasten the nuts. The whole strengthening procedure took 82 min which is equivalent to 3.5 min per installed screw. The strengthening system was installed under realistic conditions by drilling and fastening.
overhead. In addition to the speed of installation, another major advantage of the system is that the screws will immediately strengthen the concrete member and are able to take loads.

### 3 | EXPERIMENTAL RESULTS

#### 3.1 | Load-deflection behavior

Table 3 summarizes the main results of the punching shear tests. The displacement \(w_m\) describes the vertical displacement between the center of the slabs top surface and the 12 surrounding support points at the highest load. The values \(\psi_{x,out}\) and \(\psi_{y,out}\) describe the slabs rotation outside the punching shear zone in x- and y-direction, determined via the measured displacements of the sensors U6 and U7 respectively U2 and U3 in Figure 8 as follows \(\psi_{x,out} = (w_6 + w_7)/1,600\) and \(\psi_{y,out} = (w_2 + w_3)/1,600\). The rotation \(\psi_0\) is the rotation between the center of the slab and the support points and is defined by \(w_m = w_9\) and \(b_q\) in the form \(w_m/(0.5 \times b_q)\). \(V_u\) is the highest reached force at the column stub. The ratio \(V_{flex}/V_u\) serves as a characteristic to distinguish between punching failure and flexural failure. Values greater than 1 indicate punching shear failure. \(V_{flex}\) is calculated according to the yield-line theory (refer to Equation (1)).

\[
V_{flex} = 2\pi \cdot \frac{b_a}{b_q-b_c} \cdot m_R
\]

In Equation (1), \(m_R\) describes the nominal moment capacity of the slab per unit width.

The load-deformation relationship is shown in Figure 9. In series 2016, the specimens without any shear reinforcement, S01-P00 and S01-P04, show a very brittle failure behavior. After reaching the punching resistance, the load decreased abruptly. The achieved resistance of specimen S01-P00 was higher than expected. For that reason, it was decided to keep also specimen S01-P04 unstrengthened. The mean value of both failure loads was 699 kN and was used as reference load level to describe the strengthening effect. With exception of test S01-P02, the use of post installed concrete screws led to a less brittle failure mode, which is shown by the slightly rounded load–displacement curves at the level of the maximum load. In test S01-P02, the anchors were screwed up only to the lower face of the flexural reinforcement and the punching shear resistance was 21% lower than the other tests, indicating a more brittle failure behavior.

#### Table 3  Test results

| Year | Test ID   | \(w_m\) (mm) | \(\psi_{x,out}\) (mrad) | \(\psi_{y,out}\) (mrad) | \(\psi_0\) (mrad) | \(V_u\) (kN) | \(V_{flex}/V_u\) (kN) |
|------|-----------|--------------|--------------------------|--------------------------|----------------|-------------|-------------------|
| 2016 | S01-P00   | 12.65        | 11.36                    | 11.62                    | 10.54          | 720         | 1.80              |
|      | S01-P01   | 17.29        | 14.78                    | 15.50                    | 14.41          | 858         | 1.50              |
|      | S01-P02   | 14.82        | 13.02                    | 14.21                    | 12.35          | 843         | 1.57              |
|      | S01-P03   | 23.75        | 20.06                    | 21.44                    | 19.80          | 986         | 1.32              |
|      | S01-P04   | 10.73        | 9.92                     | 9.67                     | 8.94           | 677         | 1.92              |
| 2017 | S02-P01   | 20.04        | 16.47                    | 17.62                    | 16.70          | 899         | 1.64              |
|      | S02-P02   | 24.06        | 19.99                    | 21.09                    | 20.05          | 984         | 1.49              |
|      | S02-P03   | 17.90        | 16.08                    | 15.54                    | 14.92          | 860         | 1.70              |
|      | S02-P04\(^a\) | 26.81        | 25.72                    | 23.36                    | 22.34          | 908         | 1.63              |
|      | S02-P05\(^b\) | 25.31        | No data                  | 26.50                    | 21.09          | 903         | 1.64              |
| 2018 | S03-P01   | 24.54        | 22.60                    | 23.59                    | 20.45          | 990         | 1.48              |
|      | S03-P02   | 31.12        | 29.40                    | 26.06                    | 25.94          | 1,090       | 1.34              |
|      | S03-P03   | 29.01        | 27.97                    | 26.10                    | 24.18          | 896         | 1.28              |
|      | S03-P04   | 35.50        | 31.63                    | 30.63                    | 29.58          | 950         | 1.21              |
|      | S03-P05   | 33.66\(^c\) | 31.10                    | No data                  | 28.05\(^c\)    | 820         | 1.17              |
|      | S03-P06   | 40.73        | 38.79                    | No data                  | 33.94          | 821         | 1.16              |

\(^a\)Cyclic loading between 300 and 600 kN, punching shear failure after 824,967 load cycles.

\(^b\)Cyclic loading between 270 and 450 kN, after 2 million load cycles loading up to failure.

\(^c\)Due to failure of the displacement transducer, \(w_m\) is replaced by \(w_c\).
higher than the mean value of the unstrengthened reference tests. But the reached resistance was only 2% lower than the test of S01-P01 which had screws up to the top layer of the flexural reinforcement. By increasing the number of screws from 32 to 48 TSM-B22 in S01-P03 the strengthening effect raised from 23% (S01-P01) to 41% (S01-P03).

In series 2017, the main objective was to investigate the influence of cyclic loading on the strengthening system. In addition, three tests without fatigue loading were also tested. All six specimens of this test series were strengthened with post installed concrete screws. The punching shear resistance of an unstrengthened slab was recalculated from the test results of S01-P00 and S01-P04 while taking into account the lower concrete strength in series 2017. This leads to a predicted punching shear resistance value of approx. 650 kN.

Specimen S02-P01 was strengthened with 12 screws per row and the screws were installed only to the lower side of the flexural reinforcement. With this configuration a punching shear resistance of 899 kN could be reached. By installing the screws up to the upper face of the flexural reinforcement (S02-P02) the maximum load could be increased by 9% (984 kN). In test S02-P03 the use of thinner screws of type TSM-B16 instead of TSM-B22 resulted in a decrease in punching shear resistance of only 4% (860 kN). Test S02-P04 differed from test S01-P01 by applying a cyclic load between 300 and 600 kN. This cyclic load level corresponds to 1/3 and 2/3, respectively, of the failure load of S02-P01 and led to a punching failure after 824,967 load cycles. For S02-P05 and S02-P06 the load was adjusted according to real bridge geometries and fatigue load specifications of EN 1991-2 and set to 270 kN to 450 kN. Finally, the outermost (fourth) screw ring was omitted for S02-P06. Both tests showed that neither cyclic loading on realistic load level nor omitting the outermost screw row results in any negative effect on the effectiveness of the system. Although the deformations grow during the cyclic loading, the overall deformation of the cyclic loaded tests (S02-P05 and S02-P06) as well their failure loads differ only minimal from the static loaded reference test (S02-P01).

During test S01-P03 and S02-P02 the load almost reached the nominal load of the hydraulic jack. Due to the preset tolerance range, the control system unloaded automatically. After resetting the system and reloading the specimen, punching failure occurred slightly below the previously reached load level. Therefore, it can be assumed that the automatic shutdown at initial loading occurred close before failure was due to occur.

In series 2018, three different ratios of flexural reinforcement were investigated. For each of those three ratios, two shear reinforcement specimens were

**FIGURE 9** Load–displacement curves for the punching shear tests
considered, one specimen with 8 screws per row (24 screws in total) and another with 12 screws per row (36 screws in total). The specimens with the highest ratio of flexural reinforcement (S03-P01 and S03-P02) reached the highest failure loads of this series. The deformations have the opposite trend, with increasing ratio of flexural reinforcement, the deformations decrease.

Furthermore, the results in Figure 9 indicate that with a low flexural reinforcement ratio, an increase in shear reinforcement (the number of screws) leads to a smaller increase in the ultimate load than with a high degree of flexural reinforcement. For the specimens with the highest flexural reinforcement ratio of $\rho_l = 1.39\%$ (S03-P01 and S03-P02), the failure load was increased by approx. 10% by increasing the number of screws from 8 to 12 screws per row. For the slabs with $\rho_l = 1.06\%$ (S03-P03 and S03-P04), the punching shear capacity increased 6% due to the increased number of screws. At the lowest flexural reinforcement ratio of only $\rho_l = 0.78\%$ (S03-P05 and S03-P06), no significant increase in the failure load due to an increasing number of screws could be determined. This observation, as well as the $V_{\text{flex}}/V_u$ ratio close to 1 (refer Table 3), indicates that these two plates were close to flexural failure. However, in all tests of this series it was found that an increase in the number of screws led to an increase in the deformation capacity. Thus, the displacement of the column stub under failure load increased by 21% at $\rho_l = 1.39\%$, by 16% at $\rho_l = 1.06\%$ and by 8% at $\rho_l = 0.78\%$.

3.2 | Cross sections through the specimens

Figure 10 shows the saw-cuts through the tested specimens after testing. For the unstrengthened slabs (S01-P00
FIGURE 11 Measured strains of the concrete screws in series 2016 and 2017
and S01-P04), the inclination of the punching shear cone was about 30°. For the strengthened slabs, the shear cracks were much steeper. They are starting from the edge of the column, run steeply upwards, cross the first row of screws in the area of the concrete cutting thread and then run flat outwards in the plane of the flexural tensile reinforcement. An influence of the cyclic load (S02-P04, S02-P05, and S02-P06) on the progress of the shear crack could not be determined. In the tests with the lowest flexural reinforcement ratio (S03-P05 and S03-P06), the diameter of the punching shear cone was somewhat smaller, and the delamination of the flexural reinforcement was less pronounced.

3.3 | Measured strains in the concrete screws

Figures 11 and 12 compares the measured strains of the concrete screws with the load–displacement curves of the tested specimens. In each strengthened specimen, two radial rows of screws were fitted with strain gauges. Two
oppositely arranged strain gauges were attached to each of these screws on the smooth part of the screw shaft. The screws of the first row of screws (black lines) stretch much more than the screws of the second row. In rows three and four, the lowest strains were measured. The small influence of the screws in the fourth outer row on the strengthening effect could be verified by test S02-P06. The maximum measured strains of the screws were between 0.38‰ and 0.7‰ and, therefore, clearly below their yield strain \( (\varepsilon_y \text{ of the screw with the lowest yield strain was } 2.4\%) \). A significant dependence between the measured screw strains and the varied test parameters such as number of screws per row, screw depth, screw diameter and flexural reinforcement ratio cannot be determined. However, a lower installation depth of the screws tends to result in slightly lower strains of the screws. This is shown by the comparison of the measured strains in the tests S01-P01, S01-P03, and S02-P02 (installation up to the upper face of the flexural reinforcement) with the tests S01-P02, S02-P01, and S02-P03 (installation only up to the bottom face of the flexural reinforcement) in Figure 11. The measured strains of the screws in the tests S01-P01 and S01-P03 in Figure 11 and S03-P05 and S03-P06 in Figure 12 suggest that an increase in the number of screws per row leads to a slight decrease of the screw strains. Nevertheless, the comparison of the tests S03-P01 with S03-P02 and S03-P03 with S03-P04 in Figure 12 does not confirm this assumption.

4 | CONCLUSION

The effectiveness of the strengthening method with post-installed concrete screws was investigated by punching shear tests on circular slabs. The number of screws, the installation depth, the screw diameter and the flexural reinforcement ratio were mainly the varied test parameters. In order to test the suitability of this strengthening method for the use in slabs of bridges, some tests were also carried out under a cyclical load with 2 million load cycles. The main conclusions that can be drawn from the experimental program are:

1. The post installed concrete screws lead to a significant higher punching shear resistance and deformation capacity.
2. A reduction of the screw diameter from TSM-B22 to TSM-B16 causes only a slight reduction of the punching shear resistance. This can be explained by the fact that the screws are far away from yielding and therefore the bond and anchorage conditions are decisive.
3. A reduced installation depth of the screws, only to the bottom face of the flexural reinforcement, leads to a small decrease of the strengthening effect. However, in that case the failure mode becomes more brittle relative to deeper screws. Therefore, an installation depth to the upper face of the flexural reinforcement is preferable. Nevertheless, for practical use an installation depth to the bottom face of the flexural reinforcement is more likely.
4. A high flexural reinforcement ratio has a favorable impact on the strengthening effect. The reason for this is assumed to be due to the smaller slab rotation and thus smaller transverse strains at the screw ends. However, the disadvantage of a high flexural reinforcement ratio is the lower deformability of the slab and therefore the poorer announcement of failure.
5. For low flexural reinforcement ratios, the failure mode can change from punching shear failure to flexural failure. In this case increasing the number of screws leads to no further increase of the strengthening effect. Nevertheless, the deformation capacity can be still increased.
6. The first two rows of screws close to the support are subjected to significantly higher loads than the third and fourth rows of screws around the support. Omitting the outermost fourth row has no negative effect on the effectiveness of the system.
7. Cyclic loading at typical levels of service load has no negative effect on the effectiveness of the strengthening system.
8. The installation of the strengthening system is simple due to the vertical orientation of the screws from the soffit side of the slab. Accessibility to the upper face of the slab is not required.

Numerical analyses of the tests were performed, and a design approach has been derived. The results will be published soon in an additional paper.

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NOTATION

- $b_c$: diameter of the column stub
- $b_s$: diameter of the slab
- $b_d$: diameter of the support circle
- $c_{\text{nom}}$: nominal value of the concrete cover
- $d$: measured mean value of the effective depth in both directions of the flexural reinforcement
- $d_{\text{nom}}$: nominal value of the effective depth in both directions of the flexural reinforcement
- $d_x$: measured effective depth of the flexural reinforcement in $x$-direction (first layer)
- $d_y$: measured effective depth of the flexural reinforcement in $y$-direction (second layer)
- $E_c$: modulus of elasticity of concrete at time of slab testing
- $E_{\text{sw}}$: modulus of elasticity of flexural reinforcement
- $f_{c_{\text{c,l}}}$: cube (150 mm) compressive strength 28 days after concrete (standard storage)
- $f_{c_{\text{c,cube}}}$: cube (150 mm) compressive strength at time of slab testing
- $f_c$: cylinder (150 mm/300 mm) compressive strength at time of slab testing
- $f_{\text{ct,sp}}$: splitting tensile strength at time of slab testing
- $f_t$: tensile strength of flexural reinforcement
- $f_y$: yield strength of flexural reinforcement
- $f_{y_{\text{sw}}}$: yield strength of concrete screws
- $f_{y_{\text{sp}}}$: yield strength of concrete screws
- $h$: slab thickness
- $m_R$: nominal moment capacity of the slab per unit width
- $s_x$: averaged spacing of the bars in $x$-direction
- $s_y$: averaged spacing of the bars in $y$-direction
- $V_u$: maximum load at the column stub
- $V_{\text{flex}}$: flexural capacity of the slab
- $w$: vertically displacement of the column stub and the hydraulic cylinder, respectively
- $w_{\text{m}}$: vertically center deflection of the slab surface related to the support points
- $\phi_x$: diameter of the flexural tensile reinforcement bars in $x$-direction
- $\phi_y$: diameter of the flexural tensile reinforcement bars in $y$-direction
- $\rho_x$: flexural reinforcement ratio of tensile bars in $x$-direction
- $\rho_y$: flexural reinforcement ratio of tensile bars in $y$-direction
- $\rho_{\text{m}}$: mean value of the flexural reinforcement ratio in both directions

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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