Critical view on the level of maximum punching strength of flat slabs and column bases using database evaluations

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Abstract
The level of maximum punching strength is of major importance to design highly stressed slab-column connections and to choose the type of punching shear reinforcement. Since a couple of years, there is consensus that the maximum punching strength of shear-reinforced concrete slabs can be defined as a multiple of the reference punching strength without shear reinforcement. The upper bound of this load-increasing effect depends mainly on the anchorage and arrangement of shear reinforcement elements. Despite numerous research studies and database evaluations, there are ongoing discussions regarding the final effectiveness of stirrups and double headed studs installed in flat slabs and column bases.

In this paper, a strictly filtered punching database is used to highlight the significant impact of underlying reference strength comparing the maximum load increase according to current Eurocode 2 and the draft for the next generation of Eurocode 2 (prEC2). Based on this unifying database, the origin of current discrepancies is discussed and a combination of constant lower bound coefficients with a refined formula as specified in prEC2 is proposed. Additionally, the effect of adapting current European Technical Approvals for double-headed studs and punching shear optimized lattice girders to prEC2 is shortly analyzed. A further database evaluation also allows for setting the basis for optimized detailing provisions regarding the maximum permissible diameter of shear reinforcement.

KEYWORDS
column base, database evaluation, double headed stud, Eurocode 2, flat slab, maximum punching strength, punching, reinforced concrete, shear reinforcement, stirrup

1 | INTRODUCTION

The determination of the level of maximum punching strength of shear-reinforced flat slabs and column bases defining the upper punching strength limit of slab-column connections is of major importance to design highly stressed slab-column connections and to choose the type of punching shear reinforcement. Since a couple of years, there is consensus that the maximum punching strength of shear-reinforced concrete slabs can be defined as a multiple of the reference punching strength without shear reinforcement. The upper bound of this load-increasing effect depends mainly on the anchorage and arrangement of shear reinforcement elements. Despite numerous research studies and database evaluations, there are ongoing discussions regarding the final effectiveness of stirrups and double headed studs installed in flat slabs and column bases.

In this paper, a strictly filtered punching database is used to highlight the significant impact of underlying reference strength comparing the maximum load increase according to current Eurocode 2 and the draft for the next generation of Eurocode 2 (prEC2). Based on this unifying database, the origin of current discrepancies is discussed and a combination of constant lower bound coefficients with a refined formula as specified in prEC2 is proposed. Additionally, the effect of adapting current European Technical Approvals for double-headed studs and punching shear optimized lattice girders to prEC2 is shortly analyzed. A further database evaluation also allows for setting the basis for optimized detailing provisions regarding the maximum permissible diameter of shear reinforcement.
connections has been frequently evaluated during the past decades. Yet, research and discussion in this field gain again special attention at European stage due to the current revision of Eurocode 2 design provisions providing new punching shear formulas. The maximum punching capacity \( V_{\text{max}} \) of shear-reinforced slabs is typically defined as a multiple of the reference punching strength without shear reinforcement \( V_c \) by multiplying with coefficient \( \eta_{\text{sys}} \) (\( k_{\text{max}} \) as designated by current EC2) depending on the type of shear reinforcement.\(^1\)\(^{-6}\) The calibration of coefficient \( \eta_{\text{sys}} \) is mostly of empirical nature and derived from database evaluations.\(^7\)\(^{-10}\) Accordingly, the value of \( \eta_{\text{sys}} \) strongly depends on the intended level of safety, the composition of the evaluated database and, especially, the underlying reference punching strength without shear reinforcement \( V_c \).

In addition, the achievable level of \( V_{\text{max}} \) is also affected by the detailing provisions to be complied with and the interaction with the respective required amount of integrity reinforcement.

The simple value of \( \eta_{\text{sys}} \) is nonetheless often discussed without considering these deviating boundary conditions. For example, in Great Britain it was commonly referred to a value of \( \eta_{\text{sys}} = 2.0 \) in case of stirrup-reinforced flat slabs,\(^11\) whereas in Germany the current coefficient for the same type of shear reinforcement and application was deliberately reduced to \( \eta_{\text{sys}} = 1.4.\(^10\) Nevertheless, progressive collapses of flat slab structures are not automatically to be expected in Great Britain due to a different reference value \( V_c \), available safety margins, especially on action side, and other load-increasing effects such as compressive membrane action (CMA),\(^12\) which are not included in current punching design concepts such as Eurocode 2.\(^4\) In contrast, a factor accounting for CMA is included in the next generation of Eurocode 2\(^13\) but which is primarily provided for assessment of existing structures. It must generally be stated that more progressive and precise design concepts require a more detailed but concurrently consistent analysis of the level of maximum punching strength. Moreover, different national traditions and approaches regarding the determination of \( \eta_{\text{sys}} \) at mean, characteristic, or design level further complicate the discussion.

In this paper, a systematic unifying evaluation of the level of \( V_{\text{max}} \) consistently applicable for slender flat slabs as well as compact column bases is conducted focusing on stirrups and double-headed studs (DHS) used as shear reinforcement. Based on a strictly filtered but unifying database, the level of \( \eta_{\text{sys}} \) according to current Eurocode 2 (EC2),\(^4\) EC2 in combination with the German National Annex (EC2/NAD)\(^14\) and the punching design concept of the next generation of Eurocode 2 (prEC2),\(^13\) which will directly include the application of DHS, are investigated in detail. Especially, the influence of the corresponding underlying reference punching strength \( V_c \) is systematically analyzed.

For this evaluation, coefficient \( \eta_{\text{sys}} \) is deliberately calculated following the derivation process in line with current European Technical Approvals (ETAs) of specific shear reinforcement elements and being in accordance with previous German database evaluations.\(^10\) Furthermore, the effects of the new prEC2 formulas on the specifications provided by ETAs currently required for installing DHS and lattice girders are also investigated. Moreover, an additional chapter is dealing with another database evaluation to determine the maximum permissible diameter of punching shear reinforcement and thus provides the background for corresponding detailing rules according to prEC2.

### 2 | LEVEL OF MAXIMUM PUNCHING STRENGTH

#### 2.1 | Effectiveness of shear reinforcement

The applicable maximum punching strength resistance \( V_{\text{max}} \) of shear-reinforced slab-column connections, mainly affected by shape, anchorage and detailing of the shear reinforcement, is of major importance for structural engineers.\(^2\)\(^{15-17}\) In cases of constant slab geometry and concrete strength, the level of \( V_{\text{max}} \) can be influenced by the type of shear reinforcement. According to current practice, each type of shear reinforcement exhibits a specific coefficient \( \eta_{\text{sys}} \) describing the level of \( V_{\text{max}} \) as a multiple of underlying reference punching strength \( V_c \):

\[
V_{\text{max}} = \eta_{\text{sys}} \cdot V_c
\]

(1)

The most relevant types of shear reinforcement and their corresponding range of \( V_{\text{max}} \) are summarized in Figure 1. Extensive database analyses on this topic can already be found in literature (e.g., References 7,8). Since experimental test results are subjected to a certain scattering of failure loads and finally determining the maximum load increase is always affected by defining \( V_c \), Figure 1 indicates only value ranges for each type of shear reinforcement.

The smallest increase in punching capacity is provided by single-leg links and bent-up bars resulting in a maximum load increase up to 50% if a sufficient activation of these elements is ensured by proper anchorage.\(^8\)\(^16\) Although many experimental tests with these types of shear reinforcement have been conducted over the years, it is difficult to harmonize the database analysis due to numerous anchorage variations. Slightly better results are obtained from closed or lapped stirrups ensuring effective anchorage, where a load increase of at least 40%–60% is achieved.\(^7\)\(^18\)\(^19\) DHS enable a significant load increase of 80%–100% compared to reference slabs without shear reinforcement.\(^7\)\(^8\)\(^20\)
Load increases larger than 100% are realized with punching shear optimized lattice girders, such as produced by Filigran,\textsuperscript{21,22} as long as strict detailing rules are maintained. The increase of punching load is always accompanied by an enhanced rotation capacity of the slab-column connection even though this relationship is not consistent for all types of shear reinforcement.\textsuperscript{8,16}

2.2 Definitions according to design provisions

A specific quantification of the level of $V_{\text{max}}$ depending on the type of shear reinforcement must be given in design provisions. Following the multiplier approach according to Equation (1), an overview of $\eta_{\text{sys}}$-values according to current EC2,\textsuperscript{4} EC2/NAD\textsuperscript{14} and the recent draft for prEC2\textsuperscript{13} is given in Figure 2 distinguishing between flat slabs and column bases as well as stirrups and DHS. Since current EC2 only permits stirrups and bent-up bars used as shear reinforcement, punching design with DHS is so far exclusively regulated by ETAs.\textsuperscript{23,24}

A discussion of $\eta_{\text{sys}}$-values according to current EC2 and EC2/NAD can for example be found in References 5,10,25–27. The determination of $\eta_{\text{sys}}$ for DHS according to ETAs is based on statistical evaluations of the $V_{\text{max,test}}/V_{c,\text{calc}}$-ratio which is explained more detailed in Section 4.4. In contrast to these simply constant $\eta_{\text{sys}}$-values, the recent draft for prEC2 provides a novel, refined approach to determine $\eta_{\text{sys}}$:

$$\eta_{\text{sys}} = 1.15 \cdot \frac{d_{\text{sys}}}{d_{v}} + 0.63 \cdot \left( \frac{b_{0}}{d_{v}} \right)^{1/4} - 0.85 \cdot \frac{s_{0}}{d_{\text{sys}}}$$ \hspace{1cm} (2)

where $d_{v}$ is the shear-resisting effective depth, $d_{\text{sys}}$ is the shear-resisting effective depth accounting for the anchorage of shear reinforcement, $b_{0}$ is the control perimeter along the column edge and $s_{0}$ is the radial spacing of the first row of shear reinforcement to the column edge.

Apart from explicitly considering $s_{0}$ in this refined formula, the higher level of $V_{\text{max}}$ of DHS compared to stirrups is primarily a consequence of larger $d_{\text{sys}}$-values due to the anchorage conditions. The resulting range of values of $\eta_{\text{sys}}$ according to prEC2 is indicated in Figure 2 based on the different parameters emerging from the database selection used in the subsequent sections. Accordingly, comparatively large $\eta_{\text{sys}}$-values are identified for effectively anchored stirrups ($\eta_{\text{sys,stir}} = 1.5–1.95$), while smaller scattering is observed for slabs reinforced with DHS ($\eta_{\text{sys,DHS}} = 1.65–1.8$). For comparison, the constant $\eta_{\text{sys}}$-values used in former draft versions of prEC2\textsuperscript{28} are also depicted in Figure 2 ($\eta_{\text{sys,stir}} = 1.5$ and $\eta_{\text{sys,DHS}} = 1.8$).

It must be noted that Equation (2) is very sensitive to small changes of its components, although a precise prediction of $d_{\text{sys}}$ during design process is not simply possible due to constructional inaccuracies and missing detailed information about the effective anchorage height defining $d_{\text{sys}}$ in most of punching test reports referred to for database evaluations. Furthermore, it must again be emphasized that the level of $\eta_{\text{sys}}$ according to each design provision is determined with regard to a different reference value $V_{c}$. Therefore, this influence on the finally resulting level of $V_{\text{max}}$ is analyzed in more detail in chapter 4.

2.3 Discussion of safety level

Looking more precisely at the design provisions, coefficient $\eta_{\text{sys}}$ is always referred to the design level of punching capacities ($V_{\text{Rd,max}} = \eta_{\text{sys}} \cdot V_{\text{Rd,c}}$). Therefore, it may be questioned to which safety level $\eta_{\text{sys}}$...
may be related to or be derived from, respectively. A simple answer is not to be found at this point as different approaches were used in the past causing the difficult discussions at European level. According to the evaluation procedure providing the basis for current ETAs, coefficient $\eta_{\text{sys}}$ is determined from the 5%-fractile of the quotient of experimental failure load on the level of $V_{\text{max}}$ and calculated reference strength resulting from EC2 on characteristic safety level:

$$\eta_{\text{sys,ETA}} = \frac{5\%_{\text{fractile}} (V_{\text{max,test}}/V_{Rk,c,\text{calc}})}{} \quad (3)$$

In contrast to actual practice shown by Equation (3), which leads, for example, to the well-known coefficient of $\eta_{\text{sys}} = 1.96$ for DHS in flat slabs, corresponding European Assessment Documents (EADs) comprehensibly require dividing by the design value $V_{Rd,c,\text{calc}}$. As a consequence, $\eta_{\text{sys}}$ would increase by a factor of $\gamma_c = 1.5$ for current EC2 leading to significantly more progressive design results for the level of $V_{\text{max}}$. This different perspective on determining $\eta_{\text{sys}}$ with regard to the safety level may also be the reason for the dissimilar provided value for stirrups of $\eta_{\text{sys}} = 2.0$ in Great Britain in comparison to $\eta_{\text{sys}} = 1.4$ in Germany. There is no clear solution which approach might be right or wrong so that at least pointing out this complex issue is in the scope of this paper. Thus, a corresponding, uniform definition of $\eta_{\text{sys}}$ on European stage would have to be established in the future to clarify the approach with regard to the targeted safety level. Perhaps, a basic evaluation totally on mean value level in conjunction with sophisticated reliability analyses would actually be a more precise approach. For the following database evaluation, coefficient $\eta_{\text{sys}}$ is deliberately determined applying the characteristic reference strength $V_{Rk,c}$ according to Equation (3) and the evaluation procedure for current ETA provisions to ensure comparability.

### 3 DATABASES FOR FLAT SLABS AND COLUMN BASES

#### 3.1 General background

The compilation and evaluation of databases is a standard method to enable a comparison of a large number of experimental test results with predicted capacities to assess the suitability and reliability of design provisions. Accordingly, several databases for punching tests with and without shear reinforcement have been compiled in the past (e.g., References 32–35). Apart from collecting hundreds of punching test values, an essential component is the critical review of databases since not all punching tests found in literature can be used for evaluation. By defining filter criteria, certain test results must be excluded from evaluation if either information about important parameters is not given in the test reports, specific values are outside the definition range or the literature reference cannot be regarded as reliable. In case of compiling a more complex database for punching tests with shear reinforcement, distinguishing between the detected failure mode and the installed type of shear reinforcement is also mandatory.

The database used in this paper for evaluating the level of $V_{\text{max}}$ for the standard case of centric punching of internal columns in shear-reinforced flat slabs and column bases is mainly extracted from the general punching database of Siburg which originates from a collection of punching test results by Beutel and from a cooperation with ACI Committee 445 (Shear & Torsion). Over the years, the database has been continuously updated and critically reviewed at the Institute of Structural Concrete at RWTH Aachen University and was used for various previous evaluations (e.g., References 7,9,10,26,37). Recently, the database was set on a unifying basis for flat slabs and column bases including different types of shear reinforcement to allow for more universal evaluations of
shear-reinforced slabs.\textsuperscript{38} A more detailed explanation of most of the applied filter criteria can be found in Siburg.\textsuperscript{33}

### 3.2 Database composition and filter criteria

Very strict filter criteria are applied to the database to assess the ultimate level of maximum punching strength in detail. In contrast to previous database evaluations (e.g., References 9, 10, 33), the selected database consists exclusively of punching tests failing clearly on the level of $V_{\text{max}}$ without any transition to other failure modes, which may negatively affect the obtained level of $V_{\text{max}}$. The unifying focus is on flat slabs and column bases shear-reinforced with stirrups or DHS. A profound evaluation of slabs shear-reinforced with single-leg links is not possible because of too few appropriate punching test results. For example, the punching tests of Chana & Desai\textsuperscript{39} did not fail on the level of $V_{\text{max}}$, whereas the test results of Yamada\textsuperscript{40} are only reliable to a limited extent due to the dense uniform arrangement of hooks and their not practical anchorage. Moreover, only test series which also include a corresponding reference specimen without shear reinforcement are selected allowing for determining the reference strength $V_{c,\text{ref,test}}$ based on an experimental result. This enables an assessment of the load-increasing effect of shear reinforcement entirely based on experimentally obtained values without any influence of a theoretically determined reference strength $V_{Rk,c,\text{calc}}$, which needs to be calculated based on design formulas. In other words, the experimentally derived value of $\eta_{\text{sys,test}}$ can be compared to the semi-experimentally derived value of $\eta_{\text{sys,calc}}$ to identify and discuss the often underrated influence of underlying design formulas on the determined level of $\eta_{\text{sys}}$:

\begin{align}
\eta_{\text{sys,test}} &= \frac{V_{\text{max,test}}}{V_{c,\text{ref,test}}} \\
\eta_{\text{sys,calc}} &= \frac{V_{\text{max,test}}}{V_{Rk,c,\text{calc}}} 
\end{align}

Overall, a small but carefully selected group of 29 punching tests on shear-reinforced flat slabs and column bases remains in the strictly filtered database, which is listed in Tables 1 and 2.

**Table 1** Strictly filtered database for flat slab punching tests failing on the level of $V_{\text{max}}$ exhibiting corresponding reference tests to determine $V_c$

| Reference         | Type of shear rfct | $n_{\text{test}}$ [-] | $d$ [mm] | $a_l/d$ [-] | $f_{\text{cm,cyl}}$ [MPa] | $\rho_l$ [%] | $\rho_{sw}$ [%] |
|-------------------|--------------------|------------------------|----------|-------------|---------------------------|--------------|---------------|
| Müller et al.     | Stirrup            | 1                      | 154      | 7.5         | 32.9                      | 1.31         | 0.95          |
| Ladner            | Stirrup            | 1                      | 240      | 5.6         | 30.2                      | 1.31         | 1.39          |
| Beutel            | Stirrup            | 1                      | 190      | 5.3         | 29.8                      | 0.81         | 0.42          |
| Lips              | Stirrup            | 5                      | 208–354  | 3.6–6.9     | 32.0–39.1                 | ~1.52        | 0.79          |
| Schmidt et al.    | Stirrup            | 2                      | 224–320  | 4.7–7.0     | 32.9–34.8                 | ~1.40        | ~0.40         |
| Lips              | Double-headed studs (DHS) | 4              | 197–343  | 3.7–7.3     | 33.8–38.5                 | ~1.57        | 0.82–1.01     |
| Einpaul           | DHS                | 3                      | 200–211  | 3.0–8.8     | 30.9–37.8                 | ~1.53        | ~0.94         |
| **Total**         |                    | 17                     | 154–354  | 3.0–8.8     | 29.8–39.1                 | 0.81–1.57    | 0.40–1.39     |

*Note: $n_{\text{test}}$: number of selected punching test database entries; $d$: effective depth; $a_l/d$: shear span-depth ratio; $f_{\text{cm,cyl}}$: concrete compressive strength at day of testing (mean value); $\rho_l$: flexural reinforcement ratio; $\rho_{sw}$: shear reinforcement ratio ($\rho_{sw} = A_{sw}/(2s_a b_o)$).

**Table 2** Strictly filtered database for column base punching tests failing on the level of $V_{\text{max}}$ exhibiting corresponding reference tests to determine $V_c$

| Reference          | Type of shear rfct | $n_{\text{test}}$ [-] | $d$ [mm] | $a_l/d$ [-] | $f_{\text{cm,cyl}}$ [MPa] | $\rho_l$ [%] | $\rho_{sw}$ [%] |
|--------------------|--------------------|------------------------|----------|-------------|---------------------------|--------------|---------------|
| Ricker & Hegger    | Stirrup            | 3                      | 395      | 1.27–2.03   | 20.0–21.7                 | ~0.85        | 0.79          |
| Siburg & Hegger    | Stirrup            | 5                      | 400–590  | 1.25–2.03   | 18.4–23.7                 | ~0.85        | 0.60–0.77     |
| Simões et al.      | DHS                | 4                      | 497–516  | 1.25–1.83   | 33.9–36.6                 | ~0.75        | 1.11–1.15     |
| **Total**          |                    | 12                     | 395–590  | 1.25–2.03   | 18.4–36.6                 | 0.75–0.85    | 0.60–1.15     |

*Note: $n_{\text{test}}$: number of selected punching test database entries; $d$: effective depth; $a_l/d$: shear span-depth ratio; $f_{\text{cm,cyl}}$: concrete compressive strength at day of testing (mean value); $\rho_l$: flexural reinforcement ratio; $\rho_{sw}$: shear reinforcement ratio ($\rho_{sw} = A_{sw}/(2s_a b_o)$).
4 | EVALUATION OF MAXIMUM PERFORMANCE OF PUNCHING SHEAR REINFORCEMENT

4.1 | Applied methodology

As previously explained and indicated by Equations (4) & (5), the experimentally obtained values of \( \eta_{\text{sys,calc}} \) or \( \eta_{\text{sys,test}} \) may be significantly affected by the underlying reference punching capacity \( V_c \). To elaborate this influence in the following, the value of \( V_c \) is specifically determined using four different ways: Apart from the measured failure load of the corresponding reference specimen without shear reinforcement, the calculated capacities according to EC2,4 EC2/NAD14 and prEC213 on characteristic level are used. For EC2 and EC2/NAD, the characteristic concrete compressive strength is derived by \( f_{ck} = f_{cm} - 4 \) MPa according to EN 20646 similar as in References 9,31,33. In contrast to this, the design approach of prEC2 is calibrated by assuming \( f_{ck} = f_{cm} \) so that this basic consideration is also transferred to the calculation of \( V_{Rk,c,prEC2} \). Consequently, the presented evaluation is performed applying slightly different values for \( f_{ck} \) for the two groups of design provisions. Although the evaluation of design provisions with regard to database evaluations should primarily take place at a mean value level, the characteristic value of empirical coefficient \( C_{Rk,c} \) is applied for EC2 and EC2/NAD since the results of prEC2 can neither be clearly assigned to a characteristic nor to a mean value level. All other safety factors are consistently set to \( \gamma = 1.0 \).

The focus within the present paper is on a qualitative classification of the level of \( V_{\text{max}} \) and on identifying principle correlations. Small adjustments to the basic prEC2 formula providing \( V_c \) can be expected anyway until the final release of the next generation of EC2. It is exemplary referred to ongoing work of Ricker et al.45 and Yang et al.49 for more refined statistical evaluations and reliability analyses related to the new punching design provisions.

4.2 | Load increase with regard to the type of reference punching strength

Based on the database containing 29 punching tests, a statistical evaluation of \( \frac{V_{\text{max,test}}}{V_c} \)-ratios derived from different underlying reference values \( V_c \) and distinguishing between flat slabs and column bases as well as types of shear reinforcement is summarized in Table 3. The mean value \( \mu_x \) of each group represents the average load increase of punching tests failing clearly on the level of \( V_{\text{max}} \) compared to the applied reference strength and thus is specified as \( \eta_{\text{sys,mean}} \). For design, the 5%-fractiles \( x_{p,5\%} \) of \( \frac{V_{\text{max,test}}}{V_c} \)-ratios are used as prescribed by Eurocode 050 and as adapted in current EADs30,31 which regulate specific shear reinforcement products.23,24,29

Although EC2 and EC2/NAD do not permit the application of DHS, the corresponding load-increasing coefficient \( \eta_{\text{sys,DHS}} \) is nevertheless determined to allow for a direct comparison with experimental as well as prEC2 results. For the comparison of failure loads with related reference strengths without shear reinforcement, slightly scattering values for \( d, f_{ck} \) or \( \rho_l \) are standardized according to their impact in EC2 punching design formulas.

For stirrup-reinforced flat slabs, the detailed analysis reveals nearly similar \( \eta_{\text{sys}} \)-values for all four ways of determining \( V_c \) resulting in \( \mu_x \approx 1.65 \) and \( x_{p,5\%} \approx 1.40 \) indicating an almost identical reference strength \( V_c \). Hence, the reduction of \( \eta_{\text{sys}} = 1.5 \) for EC2 down to \( \eta_{\text{sys}} = 1.4 \) according to EC2/NAD derived from a strict 5%-fractile evaluation10 is confirmed. Larger differences are observed for stirrup-reinforced column bases. Apart from the incomprehensible results according to EC2 due to the additional concrete compressive strut limitation, prEC2 provides the largest \( \eta_{\text{sys}} \)-values \( \mu_x \approx 1.66 \) compared to EC2/NAD \( \mu_x \approx 1.46 \) and the experimentally derived results \( \mu_x \approx 1.56 \). This is a consequence of prEC2 underestimating \( V_c \) in column bases to a certain extent as stated in References 18,37,38, whereby direct soil pressure was consistently considered within 0.5\( d \) from column edge for prEC2. In general, similar observations are made for slabs shear-reinforced with DHS. For flat slabs, a nearly identical mean value of \( \mu_x \approx 1.95 \) is determined, while the 5%-fractile ranges between \( x_{p,5\%} \approx 1.65 \) and 1.72. The evaluation of column bases reinforced with DHS, only derivable from one single test series,45 exhibits a greater scatter. Whereas the \( \frac{V_{\text{max,test}}}{V_c,\text{ref,test}} \)-ratio provides a mean value of \( \mu_x \approx 1.47 \), the evaluation with respect to the reference value \( V_c \) of prEC2 results in a larger mean value of \( \mu_x \approx 2.09 \). Although both values are derived from the same punching tests, the calculated \( \eta_{\text{sys}} \)-values differ significantly due to the influence of \( V_c \).

A visualization of the exclusively experimentally derived mean values for \( \eta_{\text{sys,test}} \) based on the 29 selected punching tests depending on four main parameters is provided in Figure 3. The additionally plotted and nearly horizontally running trend lines for all tests with stirrups (green) indicate that the level of \( \eta_{\text{sys,test}} \) is almost independent from \( d, a_o/d, u_o/d \) or \((s_0+s_1)/d \) (with \( s_1 \) representing the radial spacing between 1st and 2nd row of shear reinforcement). For tests shear-reinforced with DHS (red), inclined trend lines are observed due to smaller \( \eta_{\text{sys}} \)-values for the four column base test results.
TABLE 3  Statistical evaluation of $V_{\text{max,test}}/V_{(Rk,c)}$-ratios providing the maximum punching performance of stirrups and double-headed studs (DHS) related to different reference punching capacities

|                  | $n_{\text{test}}$ | $V_{(Rk,c)}$ according to | $\mu_{x}$ | $V_{x}$ | $x_{p,5\%}$ |
|------------------|-------------------|-----------------------------|-----------|---------|-------------|
| **Stirrups**     | Flat slabs        | 10                          | **Reference test** | 1.62    | 0.07        | 1.43        |
|                  |                   | EC2                         | 1.67      | 0.09    | 1.41        |
|                  |                   | EC2/NAD                     | 1.66      | 0.10    | 1.39        |
|                  |                   | prEC2                       | 1.63      | 0.09    | 1.37        |
|                  | Column bases      | 8                           | **Reference test** | 1.56    | 0.13        | 1.21        |
|                  |                   | EC2                         | 2.78      | 0.14    | 2.12        |
|                  |                   | EC2/NAD                     | 1.46      | 0.06    | 1.31        |
|                  |                   | prEC2                       | 1.66      | 0.05    | 1.53        |
| **Column bases** | Flat slabs        | 7                           | **Reference test** | 1.93    | 0.07        | 1.68        |
|                  |                   | EC2                         | 1.97      | 0.09    | 1.65        |
|                  |                   | EC2/NAD                     | 1.98      | 0.09    | 1.68        |
|                  |                   | prEC2                       | 1.94      | 0.07    | 1.72        |
|                  | Column bases      | 4                           | **Reference test** | 1.47    | 0.07        | 1.28        |
|                  |                   | EC2                         | 1.92      | 0.10    | 1.59        |
|                  |                   | EC2/NAD                     | 1.75      | 0.08    | 1.50        |
|                  |                   | prEC2                       | 2.09      | 0.08    | 1.78        |

Note: $n_{\text{test}}$: number of selected punching test database entries; $\mu_{x}$: mean value of $V_{\text{test}}/V_{(Rk,c)}$-ratios; $V_{x}$: corresponding coefficient of variation; $x_{p,5\%}$: 5%-fractile of $V_{\text{test}}/V_{(Rk,c)}$-ratios.

FIGURE 3  Comparison of maximum performance of stirrups and double-headed studs (DHS) related to reference strength without shear reinforcement derived from reference punching test
Overall, a clearly higher level of $\eta_{\text{sys, test}}$ for DHS compared to stirrups is confirmed for flat slabs, while no significant difference can be stated for column bases.

In comparison, Figure 4 shows the development of $\eta_{\text{sys, calc}}$ derived from the reference value $V_{Rk,c}$ according to prEC2 focusing on the parameters $d$ and $a_0/d$. While the conclusion for stirrup-reinforced slabs remains unchanged compared to Figure 3, even slightly increasing $\eta_{\text{sys, calc}}$-values are now identified for the four column base tests with DHS. As a consequence, for prEC2 punching design, the aforementioned underestimation of $V_{Rk,c}$ entails the favorable consequence that constant $\eta_{\text{sys}}$-values for slender flat slabs as well as compact column bases seem to be permitted for each type of shear reinforcement, although a slightly smaller maximum load increase is experimentally detected in compact slabs.

### 4.3 Discussion of the next generation of Eurocode 2

The aforementioned empirical evaluation of $\eta_{\text{sys}}$, providing a unifying perspective on the maximum load increase for different boundary conditions, can be used to assess the refined $\eta_{\text{sys}}$-formula according to the next generation of EC2 (prEC2). Applying Equation (2) on the group of the 29 selected punching tests from the database (excluding two specimens with $s_0 < 0.3d$) results for flat slabs on average in $\eta_{\text{sys, stir}} = 1.78$ for effectively anchored stirrups and $\eta_{\text{sys, DHS}} = 1.88$ for DHS, whereas the column base parameters lead to $\eta_{\text{sys, stir}} = 1.69$ and $\eta_{\text{sys, DHS}} = 1.76$. For calculation, it is assumed that effectively anchored stirrups enclose the longitudinal flexural reinforcement bars resulting in $d_{\text{sys, stir}} = d_v$, whereas the DHS are anchored at the height of the outer edge of the two-layer flexural tensile reinforcement leading to $d_{\text{sys, DHS}} = d_v + \frac{\Omega}{\phi_v}$. Slightly smaller $\eta_{\text{sys}}$-values for column bases compared to flat slabs are a consequence of considering the actual $b_0/d_v$ and $s_0/d_{\text{sys}}$-ratios. Looking at these results, it is apparent that the difference between stirrups and DHS becomes considerably smaller than expected comparing with previous evaluations (see Figure 1 and Table 3). Within this context, it must again be emphasized that Equation (2) is very sensitive to small changes in coefficient $d_{\text{sys}}$, as, for example, reducing $d_{\text{sys, stir}}$ in flat slabs only by 20 mm causes a significant decrease from $\eta_{\text{sys, stir}} = 1.78$ down to $\eta_{\text{sys, stir}} = 1.64$. Regarding the $V_{\text{max, test}}/V_c$-ratios given in Table 3, the refined $\eta_{\text{sys}}$-formula seems to provide results on the mean value level $\mu_x$ not following the comparatively strictly 5%-fractile definition used for current ETAs.

Overall, the refined $\eta_{\text{sys}}$-formula provides the advantage that a more precise determination of the level of $V_{\text{max}}$ on a consistent basis for flat slabs and column bases is possible by considering favorable $b_0/d_v$ or $s_0/d_{\text{sys}}$-ratios, which are not represented by available punching tests but relevant for practical purposes. Regarding the practical point of view, a precise prediction of governing parameter $d_{\text{sys}}$ appears to be difficult, and a simple estimation of $V_{\text{max}}$ for predimensioning based on constant $\eta_{\text{sys}}$-values is not possible anymore. For all these reasons, a combination of constant lower bound values for $\eta_{\text{sys}}$ depending on the type of shear reinforcement with the refined formula according to Equation (2) allowing for more progressive results would be preferable as amendment for prEC2. Providing that these constant, lower bound $\eta_{\text{sys}}$-values should, on the safe side, be derived from 5%-fractiles and also with regard to $V_{Rk,c}$, the database evaluation results in $\eta_{\text{sys, stir}} = 1.4$ and $\eta_{\text{sys, DHS}} = 1.88$.
DHS = 1.75, which is below the values of $\eta_{\text{sys,stir}} = 1.5$ and $\eta_{\text{sys,DHS}} = 1.8$ as mentioned in former prEC2 draft versions. In the future, extensive reliability analyses are required to agree upon a uniform safety level for deriving $\eta_{\text{sys}} (V_c)$ on characteristic or design level and using the mean level or 5%-fractiles of $V_{\text{max,test}} / \mu_{V_c}$-ratios) as a considerably contribution of safety may already be included in the basic value of $V_c$.

4.4 Effect on ETAs for double headed studs and lattice girders

Currently, the maximum performance of specific shear reinforcement elements such as DHS or lattice girders is regulated in corresponding ETAs for each individual manufacturer. The coefficients $\eta_{\text{sys}}$ specified in ETAs were empirically derived as indicated by Equations (2) & (4) applying current EC2 to determine $V_{\text{Rk,c}}$. Consequently, the well-known coefficients for flat slabs of $\eta_{\text{sys}}$ for DHS = 1.96 for DHS (e.g., References 23,24) and $\eta_{\text{sys}}$, Filigran = 2.10 for punching shear optimized lattice girders29 need to be adjusted to the modified reference value $V_{\text{Rk,c}}$ according to prEC2 after its release. Industrially sponsored ETA punching tests are not part of the selected database from Section 3, and, anyway, only a fraction of corresponding ETA test results is publicly available in literature. Due to implementing the application of DHS directly in prEC2, corresponding ETAs will no longer be necessarily required. Therefore, it is of interest whether the future use of ETAs along with stricter detailing rules can or should, respectively, allow more progressive design results than the general prEC2 provisions.

To evaluate the effect of adapting $\eta_{\text{sys}}$ specified by ETAs from underlying EC2 to new prEC2 design provisions, two experimental campaigns analyzing the maximum performance of DHS and one test series investigating the load-increase of lattice girders are sufficiently reported in literature. This database of industrially sponsored punching tests failing on the level of $V_{\text{max}}$ includes five tests of Ancoplus' and seven tests of Peikko51 for DHS as well as a test series of five flat slabs with punching shear optimized lattice girders funded by Filigran.51 Reference specimens without shear reinforcement were generally not conducted within these test series. The following evaluation is focused on flat slabs as almost no experimental ETA test results on shear-reinforced column bases are available, apart from Simões et al.45 A comparison of statistically evaluated $V_{\text{max,test}} / V_{\text{Rk,c}}$-ratios derived from current ETAs (based on EC2/NAD) and recent prEC2 design provisions is given in Table 4.

The higher level of $V_{\text{max}}$ for punching shear optimized lattice girders compared to DHS is evident. Furthermore, the derivation of $\eta_{\text{sys}}$-values based on 5%-fractiles according to current ETAs is clearly verified for both types of shear reinforcement. With respect to prEC2, the mean value $\mu_x$ of $V_{\text{max,test}} / V_{\text{Rk,c}}$-ratios decreases by ~9% for DHS and by ~5% for lattice girders. In other words, an increase of $V_{\text{Rk,c}}$ leads to a reduced calculated coefficient $\eta_{\text{sys}}$. This increase of $V_{\text{Rk,c}}$ according to prEC2 is a consequence of an unlimited size effect in case of small effective depths and thus is more pronounced for high shear span-depth ratios, which is also in line with the corresponding trend lines plotted in Figure 5. The two influencing factors $d$ and $a_s / d$ cannot be evaluated separately since smaller effective depths are automatically associated with larger slab slenderness due to limited test setup dimensions. Decreasing $\eta_{\text{sys}}$-values for increasing slab slenderness were also previously observed by Peikko.51 Generally, it must also be noted that about half of the increase of $V_{\text{Rk,c}}$ from EC2/NAD to prEC2 is a consequence of the differently determined characteristic concrete compressive strength (EC2/NAD: $f_{\text{ck}} = f_{\text{cm}} - 4$ MPa; prEC2: $f_{\text{ck}} = f_{\text{cm}}$; see section 4.1).

As a matter of fact, the $\eta_{\text{sys}}$-Values accounting for the maximum performance of ETA products and following the strict 5%-fractile approach would have to be stringently reduced to $\eta_{\text{sys,DHS}} = 1.69$ for DHS and $\eta_{\text{sys,Filigran}} = 1.91$ for punching shear optimized lattice girders just due to the influence of underlying $V_c$. Despite of slightly stricter detailing rules of ETA design provisions compared to the more diverse database from Section 4.2, an even slightly reduced level of $\eta_{\text{sys}}$ for DHS is detected (see Table 3 with $\eta_{\text{sys,DHS}} = 1.72$). Consequently, the benefit of manufacturers selling DHS on the basis of a current ETA may get lost by introducing prEC2 according to the accessible database. On the contrary, applying the refined $\eta_{\text{sys}}$-formula of prEC2 on the punching tests listed in Table 4 results in even larger values of $\eta_{\text{sys,DHS,refined}} \approx 1.9$ for DHS. A calculated maximum load increase for lattice girders cannot be determined with Equation (2) since dealing with coefficient $\sigma_0$ in case of lattice girders is not yet defined. Comparing the empirical and the calculated $\eta_{\text{sys}}$-value for DHS reveals that rigorously adopting ETA rules on new prEC2 leads to a significant smaller maximum load increase than the refined $\eta_{\text{sys}}$-formula. This may be a consequence of different targeted safety levels as current ETAs follow a strict characteristic (5%-fractile) approach, whereas prEC2 pursues a mean level concept. Regarding the further discussion at European stage of specifying $\eta_{\text{sys}}$ for any type of shear reinforcement, the calibration of empirical and/or theoretically derived $\eta_{\text{sys}}$-values should definitely be established on a uniform basis, which is comparable at all.
To obtain the highest possible level of $V_{\text{max}}$, an upper limit defining the maximum permissible punching shear reinforcement diameter $\Theta_{\text{sw, max}}$ should be given in design provisions to guarantee sufficient and uniform activation of shear reinforcement. Few shear reinforcement elements with large diameters but large spacing to adjacent bars negatively affect the resulting punching load, even if allowable maximum tangential spacing are not exceeded. Previous investigations already indicated the positive impact of finely distributed shear reinforcement elements.\cite{esch, roosen} However, systematic test series usable for quantifying the influence of $\Theta_{\text{sw, max}}$ are not available so that at least more general database evaluations can be conducted to derive application limits and to assess current detailing provisions. Of course, stricter detailing rules regarding the allowable tangential spacing could also substitute the limitation of $\Theta_{\text{sw, max}}$. However, a focus on limiting $\Theta_{\text{sw, max}}$ has two advantages: Primarily, no systematic experimental evidence evaluating different tangential spacing can be found at all so that proposing a stricter limit would be more like a subjective assessment. Secondly, the limit of $\Theta_{\text{sw, max}}$ is very easy to understand and to apply in daily engineering practice.

The general punching database already referred to in this paper was used in CEN/TC250/SC2/WG1/TG4 to define the upper limit of $\Theta_{\text{sw}}$ for prEC2. For this purpose, all tests failing with any kind of punching failure inside or outside the shear-reinforced zone or on the level of $V_{\text{max}}$ were selected for evaluation to get an overview of experimentally tested values of $\Theta_{\text{sw}}$. Considering deviating anchorage conditions of different types of shear reinforcement, three different categories distinguishing between stirrups, DHS and single-leg shear links were defined for prEC2. Other shear reinforcement elements that cannot be clearly classified and specific types such as bent-up bars or I-beam section cuts were excluded for evaluation. A summary of all selected punching tests is given in the appendix in Table A1.

| $n_{\text{test}}$ | $V_{(Rk,c)}$ according to | $\mu_x$ | $V_x$ | $x_{p,5\%}$ |
|-------------------|--------------------------|---------|------|-------------|
| DHS (Ancoplus & Peikko) | Flat slabs 12 ETA (EC2/NAD) | 2.17 | 0.06 | 1.93 |
| | | 1.97 | 0.08 | 1.69 |
| Lattice girders (Filigran) | Flat slabs 5 ETA (EC2/NAD) | 2.29 | 0.05 | 2.09 |
| | | 2.15 | 0.06 | 1.91 |

Note: $n_{\text{test}}$: number of selected punching test database entries; $\mu_x$: mean value of $V_{\text{test}}$/ $V_{(Rk,c)}$-ratios; $V_x$: corresponding coefficient of variation; $x_{p,5\%}$: 5%-fractile of $V_{\text{test}}$/ $V_{(Rk,c)}$-ratios.

FIGURE 5 Comparison of maximum performance of double-headed studs (DHS) and lattice girders related to prEC2 derived from publicly accessible European Technical Approval (ETA) test results
5.2 | Discussion of maximum limits

Evaluating and deriving $\varnothing_{sw,\text{max}}$ depending on the slab’s effective depth turned out to be the most suitable method as the $\varnothing_{sw}/d$-ratio strongly influences the bond conditions and thus the activation of punching shear reinforcement. Figure 6 visualizes the database selection and also depicts the corresponding permissible upper limits according to MC2010, EC2/NAD and the current draft of prEC2.

The point cloud evolving from the selected punching tests reveals a degressive trend of the upper limit of tested $\varnothing_{sw}$ for increasing $d$ and indicates that better anchorage of shear reinforcement may go along with larger permissible bar diameters. Slabs reinforced with stiffly anchored DHS principally featured larger diameters than slabs with stirrups. The filtered database for shear links is small and represents only a very limited range of $d$. It is now interesting to compare the database with current detailing provisions. The stepwise graduated upper limit for $\varnothing_{sw,\text{max}}$ according MC2010 does not distinguish between the types of shear reinforcement and only reflects DHS adequately. Whereas general EC2 does not mention any upper limit for $\varnothing_{sw}$ at all, EC2/NAD provides a linear relationship for stirrup-reinforced slabs resulting in overestimating $\varnothing_{sw,\text{max}}$ for larger values of $d$ compared to the experimentally tested values. The prEC2 square root approach, recently defined by CEN/TC250/SC2/WG1/TG4 using the presented database, represents the upper limit quite well by introducing simple factors to differentiate between the three shear reinforcement categories (formula implemented in Figure 6).

An additional limitation ensuring proper anchorage of shear reinforcement in slabs is the minimum slab height specified as $h_{\text{lab}} \geq 200$ mm according to EC2, EC2/NAD and prEC2 or alternatively defined as $d_v \geq 160$ mm according to MC2010 which is also plotted in Figure 6.

All in all, the presented database evaluation allows for a more profound definition of $\varnothing_{sw,\text{max}}$ replacing the roughly estimated upper limits of MC2010 or EC2/NAD and paving the way for the novel prEC2 approach, which enables a straightforward determination of $\varnothing_{sw,\text{max}}$. The stricter limits for larger effective depths accounting for stirrups and single-leg shear links are also justified as the more progressive design results of prEC2 in case of shear-reinforced column bases lead to more pronounced steel stresses requiring sufficient anchorage. Future punching test series with systematically varying $\varnothing_{sw}$ in combination with different tangential spacing and types of shear reinforcement may allow for deriving more progressive upper limits for $\varnothing_{sw}$. Then, the interaction between $\varnothing_{sw,\text{max}}$ and allowable tangential spacing could also be evaluated to derive optimized and especially consistent detailing provisions.

6 | SUMMARY AND CONCLUSIONS

The discussion of the level of maximum punching strength presented in this paper provides a unifying, more universal perspective than previous evaluations.
Overall, the following essential conclusions can be drawn:

- The level of maximum punching strength mainly depends on the anchorage as well as arrangement of shear reinforcement and is commonly defined as multiple of underlying reference strength leading to $V_{\text{max}} = \eta_{\text{sys}} \cdot V_c$.

- The maximum load-increasing effect of shear reinforcement $\eta_{\text{sys}}$ can be obtained either absolutely empirically ($V_{\text{max,\text{test}}}/V_{\text{c,ref,\text{test}}}$) or with regard to a calculated reference strength ($V_{\text{max,\text{test}}}/V_{\text{c,calc}}$) or totally based on calculated capacities ($V_{\text{max,calc}}/V_{\text{c,calc}}$). Consequently, the level of resulting $\eta_{\text{sys}}$ is strongly influenced by the corresponding underlying $V_c$.

- A strictly filtered database focusing on punching tests with stirrups and DHS failing clearly on the level of $V_{\text{max}}$ allows for comparing differently derived values of $\eta_{\text{sys}}$. Regarding the empirical approach, a less pronounced load increase is observed for column bases compared to flat slabs. In contrast, constant maximum load increases independent of the type of slab can be detected for prEC2 due to underestimating underlying $V_{\text{c,calc}}$ for column bases according to prEC2.

- The refined $\eta_{\text{sys}}$-formula of recent prEC2 draft enables a more precise prediction of $\eta_{\text{sys}}$ but is not necessarily of practical nature. Therefore, conservatively derived constant lower bound values of $\eta_{\text{sys}} = 1.4$ for stirrups and $\eta_{\text{sys}} = 1.75$ for DHS in combination with the refined formula, which enables more progressive design results, are proposed as amendment for prEC2.

- Adapting current ETA provisions to the new punching design of prEC2 based on a strict 5%-fractile derivation results in reduced coefficients of $\eta_{\text{sys}} = 1.69$ for DHS and $\eta_{\text{sys}} = 1.91$ for punching shear optimized lattice girders.

- Future discussions about the derivation and calibration, respectively, of $\eta_{\text{sys}}$ should refer to a consistent safety concept. Whereas $\eta_{\text{sys}}$ for current ETA provisions is defined with regard to the characteristic value $V_{Rd,c}$, other evaluations applied the reference strength $V_{Rd,c}$ on design level leading to more progressive design results. Secondly, $\eta_{\text{sys}}$ can be understood either as mean value or as characteristic 5%-fractile of $V_{\text{max}}/V_c$-ratios resulting from database evaluations.

- The punching database also allows for comparing experimentally tested shear reinforcement diameters with upper limits for $O_{sw,\text{max}}$ according to current detailing provisions and sets the basis for the novel prEC2 approach. This straightforward prEC2 formula is well suited to determine $O_{sw,\text{max}}$ depending on the slab’s effective depth by distinguishing between the anchorage conditions of stirrups, DHS and single-leg shear links.

**DATA AVAILABILITY STATEMENT**

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

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**REFERENCES**

1. Fernández Ruiz M, Muttoni A. Applications of the critical shear crack theory to punching of RC slabs with transverse reinforcement. ACI Struct J. 2009;106(4):485–94.

2. Kueres D, Ricker M, Hegger J. Improved shear reinforcement for footings—maximum punching strength. ACI Struct J. 2018;115(5):1365–77.

3. Fédération internationale du béton (fib). Fib model code for concrete structures 2010. Berlin: Ernst & Sohn; 2013.

4. European Standard. Eurocode 2: Design of concrete structures—Part 1–1: General rules and rules for buildings. Incl. Corrigendum 1: EN 1992-1-1:2004/AC:2008, incl. Corrigendum 2: EN 1992-1-1:2004/AC:2010, incl. Amendment 1: EN 1992-1-1:2004/A1:2014(EN 1992-1-1:2004/A1); 2014.

5. Ricker M, Siburg C. Punching shear strength of flat slabs—critical review of Eurocode 2 and fib model code 2010 design provisions. Struct Concr. 2016;17(3):457–68.

6. Hegger J, Häusler F, Ricker M. Zur maximalen Durchstanztragfähigkeit von Flachdecken. BuSt. 2007;102(11):770–7.

7. Hegger J, Sheriff AG, Kueres D, Siburg C. Efficiency of various punching shear reinforcement Systems for Flat Slabs. ACI Struct J. 2017;114(3):631–42.

8. Einpaul J, Brantschen F, Fernández Ruiz M, Muttoni A. Performance of punching shear reinforcement under gravity loading: influence of type and detailing. ACI Struct J. 2016;113(4):827–38.

9. Kueres D, Siburg C, Herbrard M, Classen M, Hegger J. Uniform design method for punching shear in flat slabs and column bases. Eng Struct. 2017;136:149–64.

10. Siburg C, Häusler F, Hegger J. Durchstanzeigenschaften von Flachdecken nach NA(D) zu Eurocode 2. Bauingenieur. 2012;87(5):216–25.

11. Fraser A, Jones T. Effectiveness of punching shear reinforcement to EN 1992; CEN/TC250/SC2: Document N 709 (unpublished) 2008.

12. Einpaul J, Fernández Ruiz M, Muttoni A. Influence of moment redistribution and compressive membrane action on punching strength of flat slabs. Eng Struct. 2015;86:43–57.

13. CEN/TC 250/SC 2/WG 1. prEN 1992-1-1/2020–11: Eurocode 2: Design of Concrete Structures - Part 1–1: General rules for buildings, bridges and civil engineering structures. Seventh Draft by Project Team SC2.T1; 2020.

14. Deutsches Institut für Normung e.V. (DIN). Nationaler Anhang – National festgelegte Parameter – Eurocode 2: Bemessung und...
Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1–1: Allgemeine Bemessungsregeln und Regeln für den Hochbau; 91.010.30; 91.080.40 (DIN EN 1992–1–1/NA:2013–04). Berlin: Beuth; 2013.

15. Beutel R, Hegger J. The effect of Anchorage on the effectiveness of the shear reinforcement in the punching zone. Cement Concr Compos. 2002;24(6):539–49.

16. Brantschen F. Influence of bond and anchorage conditions of the shear reinforcement on the punching strength of RC slabs. PhD-Thesis. Lausanne, Switzerland; 2016.

17. Lips S. Punching of flat slabs with large amounts of shear reinforcement. PhD-Thesis. Lausanne, Switzerland; 2012.

18. Kueres D, Schmidt P, Hegger J. Punching shear behavior of reinforced concrete footings with a varying amount of shear reinforcement. Struct Conc. 2019;20(2):552–63.

19. Schmidt P, Kueres D, Hegger J. Punching shear behavior of reinforced concrete flat slabs with a varying amount of shear reinforcement. Struct Conc. 2020;21(1):235–46.

20. Lips S, Fernández Ruiz M, Muttoni A. Experimental investigation on punching strength and deformation capacity of shear-reinforced slabs. ACI Struct J. 2012;109(6):889–900.

21. Siburg C, Hegger J, Fürche J, Bauermeister U. Durchstanzbewehrung für Elementdecken nach Eurocode 2. BuSt. 2014;109(3):170–81.

22. Schmidt P, Fürche J, Bauermeister U. Orthogonale Anordnung der Filigran®-Durchstanzbewehrung. BuSt. 2019;114(7):495–504.

23. Halfen GmbH. European technical assessment ETA-12/0454: Halfen HDB: double headed studs as punching reinforcement; 2017.

24. Peikko Group. European technical assessment ETA-13/0151: Peikko PSB: double headed studs as punching reinforcement; 2018.

25. Siburg C, Ricker M, Hegger J. Punching shear design of footings: critical review of different code provisions. Struct Conc. 2014;15(4):497–508.

26. Hegger J, Walraven JC, Häusler F. Zum Durchstehen von Flachdecken nach Eurocode 2. BuSt. 2010;105(4):206–15.

27. Halvön J, Majtanová L. Experimental investigation of the maximum punching resistance of slab-column connections. Slovak J Civil Eng. 2018;26(3):22–8.

28. CEN/TC 250/SC 2/WG 1. prEN 1992–1–1/2020–06: Eurocode 2: Design of Concrete Structures - Part 1–1: General rules for buildings, bridges and civil engineering structures. Fifth Draft by Project Team SC2.T1; 2020.

29. Filigran Trägersysteme GmbH & Co. KG. European Technical Assessment ETA-13/0521: Filigran FDB: Filigran lattice girders as punching reinforcement; 2018.

30. EOTA. EAD 160055–00–0301: lattice girders for the increase of punching shear resistance of flat slabs or footings and ground slabs (EAD 160055–00–0301). Brussels, Belgium: EOTA; 2017.

31. EOTA. EAD 160003–00–0301: double headed studs for the increase of punching shear resistance of flat slabs or footings and ground slabs (EAD 160003–00–0301). Brussels, Belgium: EOTA; 2018.

32. Ospina CE, Birkle G, Widianto W, Wang Y, Fernando S.R., Fernando S., et al. ACI 445 Punching Shear Collected Databank. Available from: https://datacenterhub.org.

33. Siburg C. Zur einheitlichen Bemessung gegen Durchstehen in Flachdecken und Fundamenten. Dissertation. Aachen; 2014.

34. Muttoni A, Fernández Ruiz M, Simões JT. The theoretical principles of the critical shear crack theory for punching shear failures and derivation of consistent closed-form design expressions. Struct Concr. 2018;19(1):174–90.

35. Walkner R. Kritische analyse des Durchstanznachweises nach EC2 und Verbesserung des Bemessungsansatzes: critical review of EC2 regarding punching and improving the design approach. Dissertation. Innsbruck, Austria; 2014.

36. Beutel R. Durchstanzen schubbewehrter Flachdecken im Bereich von Innenstützen. Dissertation. Aachen; 2003.

37. Hegger J, Adam V, Schmidt M & Schmidt P Fallbeispiele, Parameterstudien und Datenbankauswertungen zu den Vorschlägen der Querkraft-, Torsions- und Durchstanzbemessung für die zweite Generation des Eurocode 2. Research Report. Aachen; 2020.

38. Schmidt P. Punching in shear-reinforced flat slabs and column bases. Dissertation. Aachen; 2021.

39. Chana PS, Desai SB. Design of shear reinforcement against punching. Struct Eng. 1992;70(9):159–64.

40. Yamada T, Nanni A, Endo K. Punching shear resistance of flat slabs: influence of reinforcement type and ratio. ACI Struct J. 1992;89(4):555–63.

41. Müller F-X, Muttoni A, Thürlimmann B. Durchstanzversuche an Flachdecken mit Aussparungen. Zürich, Schweiz; 1984.

42. Ladner M. Untersuchungsbericht Durchstanzversuche an Flachdeckenausschnitten. Schweiz: Horw; 1998.

43. EinPaul J. Punching strength of continuous flat slabs. PhD-Thesis. Lausanne, Switzerland; 2016.

44. Siburg C, Hegger J. Experimental investigations on the punching behaviour of reinforced concrete footings with structural dimensions. Struct Conc. 2014;15(3):331–9.

45. Simões JT, Bujnak J, Fernández Ruiz M, Muttoni A. Punching shear tests on compact footings with uniform soil pressure. Struct Conc. 2016;17(4):603–17.

46. CEN European Committee for Standardization. EN 206+A1: Concrete—specification, performance, production and conformity. Berlin; 2016.

47. Muttoni A, Fernández Ruiz M, Simões JT, Hegger J, Siburg C, Kueres D. Background document for section 8.4: Punching. 2017.

48. Ricker M, Feiri T, Nille-Hauf K, Adam V, Hegger J. Enhanced reliability assessment of punching shear resistance models for flat slabs without shear reinforcement: first published online. Eng Struct. 2021;226:111319.

49. Yang Y, Cesar B, Slobbe A, Rózsás Á. Reliability-based calibration of the prEN 1992–1 D4 design shear resistance formula and of the design punching shear resistance formula for members without shear reinforcement; 2020.

50. Deutsches Institut für Normung e.V. (DIN). Eurocode 0: Grundlagen der Tragwerksplanung: Deutsche Fassung EN 1990:2002 + A1:2005 + A1:2005/AC:2010/91.010.30 (DIN EN 1990:2010–12). Berlin: Beuth; 2010.

51. Muttoni A, Bujnak J. Hohe Tragfähigkeit von Decken mit PSB Durchstanzbewehrung. In Großversuchen demonstriert und nachgewiesen zur Erteilung der ETA-Zulassung. Technical Report; Concrete Connections; 2013.

52. Schmidt P, Kueres D, Hegger J. Contribution of concrete and shear reinforcement to the punching shear resistance of flat slabs. Eng Struct. 2020;203:1–11.

53. Schmidt P, Ungermann J, Hegger J. Contribution of concrete and shear reinforcement to the punching shear resistance of column bases. Eng Struct. 2021;245:1–12.
54. Elstner RC, Hognestad E. Shearing strength of reinforced concrete slabs. J Am Concr Inst. 1956;28(1):29–58.

55. Anderson JL. Punching of concrete slabs with shear reinforcement. Gothenburg, Sweden; 1963.

56. Marti P, Pralong J, Thürlimann B. Schubversuche an Stahlbeton-Platten. Birkhäuser Basel: Zürich, Schweiz; 1977.

57. Seible F, Ghali A, Dilger WH. Preassembled shear reinforcing units for flat plates. ACI J. 1980;77(1):28–35.

58. Tolf P. Plattjocklekens inverkan pa betongplattors hallfasthet vid genomstansning. Stockholm, Sweden; 1988.

59. Broms CE. Shear reinforcement for deflection ductility of flat plates. ACI Struct J. 1990;87(6):696–705.

60. Chana PS. A prefabricated shear reinforcement system for flat slabs. Proc Inst Civil Eng Struct Build. 1993;99(3):345–58.

61. Oliveira DR, Melo GS, Regan PE. Punching strengths of flat plates with vertical or inclined stirrups. ACI Struct J. 2000;97(3):485–91.

62. Regan PE, Samadian F. Shear reinforcement against punching in reinforced concrete flat slabs. Struct Eng. 2001;79(10):24–31.

63. Vollum RL, Abdel-Fattah T, Eder M, Elghazouli Ay. Design of ACI-type punching shear reinforcement to Eurocode 2. Mag Concr Res. 2010;62(1):3–16.

64. van der Voet AF, Dilger WH, Ghali A. Concrete flat plates with well-anchored shear reinforcement elements. Can J Civil Eng. 1982;9(1):107–14.

65. Mokhtar A-S, Ghali A, Dilger WH. Stud shear reinforcement for flat concrete plates. ACI J. 1985;82(5):676–83.

66. Birkle G. Punching of flat slabs - the influence of slab thickness and stud layout. PhD-Thesis. Calgary, Canada; 2004.

67. Broms CE. Ductility of flat plates: comparison of shear reinforcement systems. ACI Struct J. 2007;104(6):703–11.

68. Heinzmann D, Etter S, Villiger S, Jaeger T. Punching tests on reinforced concrete slabs with and without shear reinforcement. ACI Struct J. 2012;109(6):787–94.

69. Ferreira MP, Melo GS, Regan PE, Vollum RL. Punching of reinforced concrete flat slabs with double-headed shear reinforcement. ACI Struct J. 2014;111(2):363–74.

70. Lee SC, Lee SB, Teng S, Morley CT. Punching shear tests on high strength concrete slabs. In: Norwegian Concrete Association, ed. 5th International Symposium on Utilization of High Strength/High Performance Concrete. Oslo, Norway; 1999, p. 401–10.

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APPENDIX

Database composition for discussion of maximum bar diameters

For evaluating the maximum permissible bar diameters of punching shear reinforcement $\Phi_{sw,\text{max}}$ with regard to the slab's effective depth and distinguishing between three different anchorage categories, a total of 140 punching tests is selected, which is listed in Table A1.

**TABLE A1** Database for evaluating the maximum permissible punching shear reinforcement diameter

| Reference               | Type of shear reinforcement | $n_{\text{test}}$ [-] | $d$ [mm] | $\Phi_{sw}$ [mm] | Failure mode     |
|-------------------------|----------------------------|-----------------------|----------|------------------|------------------|
| Elstner & Hognestad     | Stirrup                    | 1                     | 114      | 9.5              | out              |
| Andersson               | Stirrup                    | 4                     | 119–120  | 6                | out              |
| Marti et al.            | Stirrup                    | 1                     | 152      | 8                | max              |
| Seible et al.          | Stirrup                    | 2                     | 121      | 5.7              | out, max         |
| Müller et al.           | Stirrup                    | 1                     | 154      | 8                | max              |
| Tolf                    | Stirrup                    | 8                     | 97–198   | 5/10             | ins, out         |
| Broms                   | Stirrup                    | 4                     | 150      | 6/8              | bet, max, out    |
| Chana                   | stirrup                    | 2                     | 240      | 10               | ins/max, out     |
| Oliveira et al.         | Stirrup                    | 3                     | 103–105  | 5/6.3            | ins, out         |
| Regan & Samadian        | Stirrup                    | 2                     | 160      | 6/8              | ins              |
| Beutel                  | Stirrup                    | 2                     | 190      | 8/10             | max, out         |
| Hegger et al.           | Stirrup                    | 1                     | 160      | 8                | max              |
| Vollum                  | Stirrup                    | 2                     | 174      | 8/10             | ins, out         |
| Lips                    | Stirrup                    | 5                     | 208–354  | 10               | ins, max         |
| Schmidt et al.          | Stirrup                    | 8                     | 224–321  | 6–14             | ins, max         |
| Siburg & Hegger         | Stirrup                    | 8                     | 395–590  | 12/14            | max              |
| Kueres et al.           | Stirrup                    | 5                     | 396–594  | 6/8/10           | ins              |
| Van der Voet et al.     | DHS                        | 6                     | 113      | 4.9–9.5          | ins, out         |
| Mokhtar et al.          | DHS                        | 7                     | 116      | 9.5              | ins              |
| Regan & Samadian        | DHS                        | 6                     | 160–164  | 10/12            | ins, out         |
| Beutel                  | DHS                        | 10                    | 250–350  | 14/16            | max              |
| Birkle                  | DHS                        | 9                     | 124–260  | 9.5/12.7         | ins, out         |
| Broms                   | DHS                        | 2                     | 141–151  | 12               | ins              |
| Heinzmann et al.        | DHS                        | 2                     | 294      | 18               | max, out         |
| Lips                    | DHS                        | 6                     | 197–343  | 10–22            | ins, max         |
| Ferreira et al.         | DHS                        | 11                    | 140–145  | 10/12.5          | ins, out         |
| Einpaul                 | DHS                        | 4                     | 200–211  | 16               | bet, max         |
| Simões et al.           | DHS                        | 4                     | 497–516  | 25               | max              |
| Chana & Desai           | Shear links                | 7                     | 188–210  | 8/10             | ins              |
| Chana                   | Shear links                | 1                     | 183      | 8                | ins              |
| Lee et al.              | Shear links                | 5                     | 155–230  | 8/10             | ins              |
| Total                   |                           | 140                   | 97–594   | 4.9–25           | ins, bet, max, out |

Note: $n_{\text{test}}$: number of selected punching test database entries; $d$: effective depth; $\Phi_{sw}$: diameter of punching shear reinforcement; failure mode: documented failure mode (ins: inside the shear-reinforced zone; max: failure on the level of $V_{\text{max}}$; out: outside the shear-reinforced zone; bet: punching failure between the shear reinforcement elements).