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Design Recommendations for Concrete Pryout Capacity of Headed Steel Studs and Post-Installed Anchors

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Abstract: Current formulas to assess the shear capacity of headed steel stud anchors and post-installed (PI) anchors in case of pryout failure (sometimes known as pull-rear failure) have been derived either based on the indirect-tension resistance model or are fully empirical based on push-out test results. In both cases, the predicted pryout capacity is clearly conservative and underestimates the true pryout capacity of anchorages, especially for stiff anchors with low embedment-to-diameter ratios ($h_{ef}/d < 4.5$). This paper proposes an empirical and a semi-empirical formula to predict the concrete pryout capacity of headed steel studs and PI anchors. They were derived based on an improved indirect-tension model which accounts for the stud diameter and the stud spacing in a group of anchors. Furthermore, a database of 214 monotonic shear tests from the literature, including own tests (push-off and horizontally shear tests), is reevaluated and compared to the provisions of EN1992-4. The scope of this assessment proposal includes single and group of headed steel studs and PI anchors attached to a stiff steel plate as well as shear connectors in composite structures without metal deck embedded in normal-weight concrete.

Keywords: pryout capacity; pryout failure; anchor group; welded studs; shear load; design formula

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1. Introduction

Concrete capacity design method (CCD method) [1] is currently the most frequently used for calculating the concrete breakout capacity of anchors or a group of anchors. Current design codes, such as EN1992-4 [2], ACI 318-19 [3], EOTA-ETAG001 [4] and fib Bulletin 58 [5], which are based on the CCD method, treat concrete cone breakout behind a single anchor or an anchor group under shear load in a way comparable to tension pull-out failure based on the indirect-tension resistance model [6]. Accordingly, the characteristic concrete pryout resistance $V_{Rk,cp}$ is calculated using the following modified mean tensile pull-out capacity equation of an anchor group away from edge effects:

$$V_{Rk,cp} = k_8 \cdot N_{Rk,c} \tag{1}$$

$$N_{Rk,c} = A_{c,N} / A^0_{c,N} \cdot N^0_{Rk,c} \tag{1a}$$

$$N^0_{Rk,c} = k_1 \cdot f_{ck}^{0.5} \cdot h_{ef}^{1.5} \tag{1b}$$

where

k_8	empirical factor indicated in the corresponding technical specifications,
$N_{Rk,c}$	characteristic concrete breakout strength of anchor group in tension,
$A_{c,N}/A^0_{c,N}$	projection area ratio of anchor group in tension,
$N^0_{Rk,c}$	characteristic concrete breakout strength of single anchor in tension away from edge influence,
k_1	empirical factor indicated in the corresponding technical specifications for cracked and uncracked concrete,
f_{ck}	characteristic cylinder compressive strength of concrete and
h_{ef}	effective embedment depth.

The applied analogy of shear load prediction to tensile pull-out capacity equation of an anchor group does not account for the anchor diameter, which is known to have a significant influence on the concrete pryout capacity. The anchor diameter influences the applied pressure on the concrete in front of the anchor bolt due to the applied shear load. In the previous study [7,8], it was shown that the pryout capacity increases proportionally to the square root of the stud/anchor diameter $\left(d^{0.5}\right)$. The existing formulation in EN1992-4 (Equation (1)) tends to over-simplify the calculation method by indirectly relating the concrete breakout strength of anchors in tension to the pryout capacity of anchors loaded in shear. This over-simplification and ignorance of relevant parameters, such as the anchor diameter and anchor spacing in the case of a group of anchors, might result in underestimation (or in some cases over-estimation) of the pryout failure loads. Moreover, it seems counter-intuitive that the use of the projection area ratio of the anchor group in tension as well as the concrete breakout strength of a single anchor in tension according to the CCD method would be directly applicable to the group of anchors under shear. In contrast, current empirical formulas to compute the concrete failure of anchors subjected to shear force are based primarily on the results of push-out tests which focused predominantly on composite beams with and without metal deck (Table 1, [9]). The AISC [10] and EN 1994-1-1 [11] formulas are an adaption of the formula for headed steel anchors in composite beams proposed by Ollgaard et al. [12] and are valid additionally for the design of composite components, such as composite columns. While the AISC formula to compute the shear strength does not have its own resistance safety factor, the EC-4 formula, in contrast, is affected by partial safety factors and the ratio of anchor height to diameter, which provide more conservative results.

Table 1. Concrete shear strength for single anchor.

	Concrete Pryout Failure Average Formula
AISC	$0.5\ A_s\ \sqrt{f_c E_c}$
EN 1994-1-1	$0.29\ \alpha\ d^2\ \sqrt{f_{ck} E_{cm}}$ $\quad \alpha = 0.2\left(\frac{h_{sc}}{d}+1\right)\ for \quad 3 \le \frac{h_{sc}}{d} \ge 4$ $\alpha = 1 \quad for \quad \frac{h_{sc}}{d} > 4$
PCI 6th	$24.3\ \lambda\ f_c^{0.5}\ d^{1.5}\ h_{ef}^{0.5}$
A_s	Anchor cross-section area
f_c	Compressive strength of concrete
$E_c : E_{cm}$	Modulus and secant modulus of elasticity of concrete
h_{sc}	Nominal anchor length
λ	Modification factor for lightweight concrete
d	Anchor diameter
h_{ef}	Effective embedment depth

The PCI 6th edition [13] and ACI 318-19 and EN 1992-4 formulas to compute the pryout resistance are based on the 5%-fractile value (characteristic value), which means that one can say with 90% confidence that 95% of the actual concrete strengths exceed this value. However, the PCI 6th edition formula takes the anchor stiffness into account and computes the pryout resistance for stiffness ratio $h_{ef}/d < 4.5$. Other than AISC and EN 1994-1-1 formulas, the PCI 6th edition formula, similar to ACI 318 and EN1992-4 formulas, is valid for headed steel studs and PI anchors, which is implemented by means of a modified pre-factor. Moreover, the PCI 6th equation was extended to account for one and multiple rows of anchors as it was introduced by Anderson and Meinheit [14]:

$$V_{u,cp} = 24.3\ n\ \lambda\ \ f_c^{0.5}\ d^{1.5}\ h_{ef}^{0.5}\ \psi_{s,\parallel}\ \psi_{s,\perp} \tag{2}$$

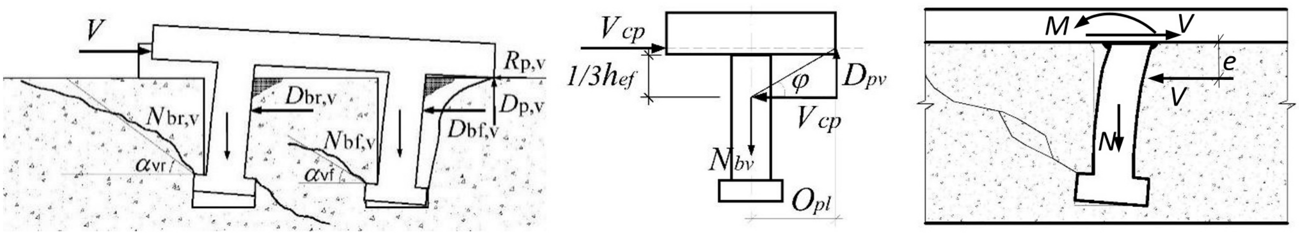
$$\psi_{s,\|} = \sqrt{S_{\|}}/4d \tag{2a}$$

$$\psi_{s,\perp} = \left(\frac{h_{ef}}{d}\right)\left(\frac{S_{\perp}}{1825} + 0.16\right) \tag{2b}$$

where n is the number of anchors in the group and ψ_s is a modification factor which accounts for the influence of the anchor spacing parallel and perpendicular to the load direction.

According to the evaluated data, it was recommended that the maximum row spacing parallel and perpendicular to loading direction should be limited to about 20d.

In a previous work by the authors [15], the concrete pryout failure mechanism for shear-loaded short single stud anchor [7] is extended to interpret the failure mechanism of the anchor group. Based on the shear load transfer of a single stud anchor and assuming that the anchor plate is stiff, the internal bearing forces in front of the studs of the anchor group as a result of the applied external shear load ensued an internal overturning moment of the anchor plate (see Figure 1a,b). The overturning moment induces a bearing pressure under the front side of the anchor plate and tensile forces in the studs. An increase in the shear load V induces a zone of crushing in front of the anchors near the concrete surface, which results in increased stud deformation and plate rotation as well. Subsequently, the overturning moment, induced by the lever arm of the tensile forces in the studs and the compression under the front side of the anchor plate, pulls out the concrete at the rear side of the studs, including the enclosed concrete between the studs. The concrete in front of the anchor group remains primarily undamaged except for some small crushing due to the bearing pressure zone in front of the anchor group induced by the overturning moment.



(**a**) (**b**) (**c**)

Figure 1. (**a**) Pryout failure mechanism of an anchor group [15,16] (**b**) Load transfer mechanism over the fastener [7] (**c**) Stud shear connector in a composite member [12,17].

Based on a relatively large experimental and numerical database, the aforementioned pryout failure mechanism and proposed mechanical model are considered valid for anchor groups with anchor spacing in the range $S/d \leq 13.5$ and $S/h_{ef} \leq 3$ with stiff (stocky) anchors ($h_{ef}/d < 4.5$) and stiff anchor plate ($t_p \geq 0.5d$) embedded in normal-weight concrete [15,16]. Moreover, the numerical investigation revealed that as the anchor plate overhang (O_{pl}) increases, the ratio of induced tensile force in the anchor to the shear force ($N_{b,v}/V_{cp}$) decreases, and the overturning moment turns into the so-called dowel action for fasteners in composite concrete structures (see Figure 1b,c). As shown in Figure 1c, the relative slip movement between the concrete and steel section in the composite beam member is resisted by the dowel action of the stud shear connector which manifests itself through shear, flexure and axial force in the stud [17].

This paper presents a new and simple to use recommendations for design of single anchors and groups of anchors (such as headed steel stud and PI anchor) with a stiff base plate against concrete pryout failure. The design method is equally applicable for composite structures without steel profile sheeting or a metal deck. This proposal is based on the equation proposed by Jebara et al. (2015) [7] for calculating the pryout resistance of single anchors. According to the proposed mechanical model, the mean concrete pryout resistance of a single anchor away from edge influence in uncracked concrete is given as follows [16]:

$$V_{Rm,cp} = k_{cp,m} \cdot d^{0.5} \cdot f_{cc}^{0.5} \cdot h_{ef}^{1.5} \tag{3}$$

where $k_{cp,m}$ is the empirical factor for pryout failure with $k_{cp,m}$ = 6 for headed studs and $k_{cp,m}$ = 5.25 for post-installed anchors, d is the nominal diameter of the anchor (mm), f_{cc} is the mean cube compressive strength of concrete (N/mm^2) and h_{ef} is the embedment depth (mm).

It should be noted that the reduction of approximately 15% of the empirical factor for post-installed anchors $k_{cp,m}$ is based on the fact that the pryout failure mode is an indirect-tension concrete failure. Therefore, it is reasonable to account for the unfavorable influence of the mechanical interlock of post-installed anchors regarding smaller activated concrete failure surface and higher concrete stresses in the load-bearing area compared to headed studs [18]. Moreover, the load-displacement behavior of PI anchors and headed studs under shear load is comparable.

Furthermore, this paper presents empirical equations to assess the limit state of concrete pryout failure of a group of anchors (headed studs and PI anchors) embedded in normal-weight concrete and subjected to static shear forces. The limit state of concrete pryout failure is assumed to be governing limit state for stocky anchors with $h_{ef}/d < 4.5$. Such groups of anchors are used both in concrete constructions with a stiff steel base plate, away from edge influence, "in the field", and in composite structures. This proposal is applicable for concrete slabs without steel profile sheeting or a metal deck as well as for composite elements, such as concrete columns, boundary elements of composite wall systems and related forms of composite construction, where stocky shear connectors are in use. Two hundred and fourteen test results (Table A1 [19–30]) of headed steel anchors (primarily push-out tests which simulate well the conditions in composite structures) and PI anchors with a stiff base plate (single and group of anchors) were collected and used to assess the concrete pryout failure according to EN 1992-4 and proposed design recommendations.

2. Concrete Pryout Prediction Equation for Anchor Groups

As mentioned above, based on detailed experimental and numerical studies, a new concrete pryout prediction proposal (see Equation (3)) for single anchors away from any other influences was proposed in [16]. Furthermore, detailed experimental and numerical investigations were followed to extend the proposal to anchor groups as presented in a previous paper by the authors [15]. The predictive equation is based on the simplified half-pyramid model adopting a failure surface angle of α_v = 30° [8,16]. Moreover, the half-pyramid concrete breakout includes the concrete wedged between the studs. Accordingly, an extended projection area including the area enclosed between the stud spacing parallel and perpendicular to the shear load direction was evaluated. Thereby, the tensile stress distribution perpendicular to the simplified truncated concrete cone surface in the case of a group of anchors has been taken into account. The projection area ratio, relating to the projection area of a single anchor, accounts for the influence of the stud spacing on the pryout capacity. It is also assumed that the effective compressive stress of an anchor group, which is the resultant tensile force in the studs divided by the projection area of the anchor group, is equivalent to the effective compressive stress of a single anchor [16]. The results of available push-off and pryout experimental tests (Appendix A) show that the pryout capacity increases with an increase in stud spacing, due to an increased concrete resistance and lever arm between the resultant tension force in the anchors and compression under the front side of the anchor plate. The results also show that the interacting stud spacing parallel and/or perpendicular to the shear load direction has an effect on the pryout capacity and failure mode. Accordingly, in general, it seems reasonable to interpret that concrete pryout failure of the anchor group is established as long as $h_{ef}/d < 4.5$ and the stud spacing in both directions $S \leq 3h_{ef}$, which can be considered as the transition into mixed or steel failure mode. Moreover, nonlinear finite element numerical investigations [8,16] and corresponding experimental results [7,8] show that the crack development in case of concrete pryout failure begins at the stud head and propagates towards the concrete surface at the back side of the anchorage. Comparable with the concrete breakout of anchor in tension, it can be concluded that the pryout capacity of the indirect-tension failure mechanism does not depend on the concrete slab thickness, provided that the thickness of the slab is sufficient to prevent splitting failure. For further information on the development of the predictive equation, reference can be made to [15,16].

3. Simplified Half-Pyramid Model Implementation

The frequently used concrete capacity design method (CCD method) for calculating the concrete cone resistance of cast-in and post-installed anchors and anchor groups loaded in tension is based on a simplified pyramid model with a pyramid surface angle of α_N~35°. The same concrete breakout pyramid surface angle is used for the obtained half-pyramid surface angle in the case of concrete pryout failure of an anchorage under shear load α_v~35°.

As previously mentioned, the available experimental results were reevaluated based on a simplified half-pyramid model for anchors loaded in shear adopting the pyramid surface angle $\alpha_v = \alpha_N = 35°$. Accordingly, the projection area of a single anchor and group of anchors failing in concrete pryout is calculated as follows (Figure 2):

$$A^0_{p,v} = 4.5 \cdot h^2_{ef} \tag{4a}$$

$$A_{p,v} = \left(S_x + 1.5h_{ef}\right) \cdot \left(S_y + 3h_{ef}\right) \tag{4b}$$

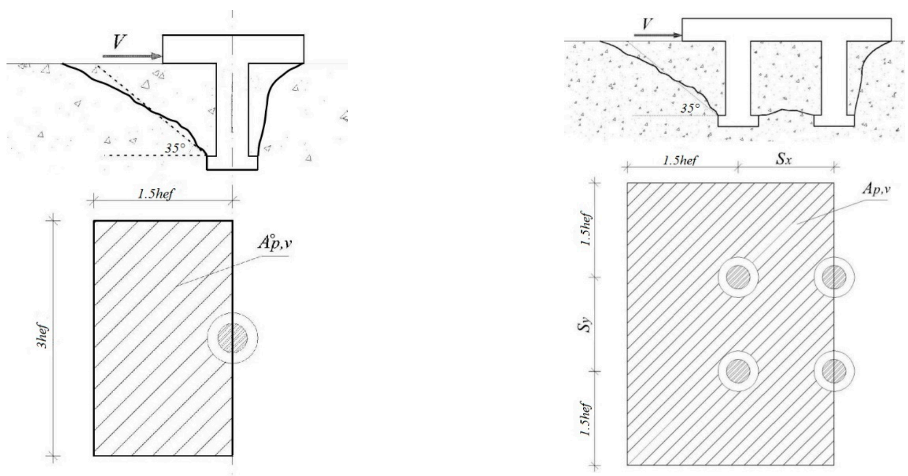


Figure 2. Projection area calculation for pryout failure mode.

S_x and S_y are the total anchor spacing distances parallel and perpendicular to the load direction. The projection area ratio could exceed the number of the studs in the connection at S_x,S_y > $2h_{ef}$. This can be explained by means of the concrete pryout mechanism of an anchor group based on the indirect tension model, which was numerically investigated in previous papers [9,16]. Accordingly, as the lever arm between the resulting tensile pull-out force and the compressive stresses under the front side of the steel anchor plate increases due to an increasing anchor spacing in the load direction, the resulting tensile forces in the studs decrease, which, in turn, leads to an increase in shear resistance.

Based on the proposed pryout capacity formula (Equation (3)) and the projection area (Equation (4)), the available test results on cast-in anchors (single anchors and group of anchors with one- and multiple-row anchorages with 2-3-4-6 and 8 anchor configurations) as well as post-installed single anchors (headed stud, undercut and bond anchor) and quadruple anchor groups (undercut, expansion and bond anchors) failing in concrete pryout and/or mixed failure mode (steel failure and concrete breakout) were evaluated according to the following equation:

$$V_{cp} = A_{p,v} / A^0_{p,v} \cdot V^0_{cp} \tag{5}$$

where $A_{p,v}$ and $A^0_{p,v}$ according to Equation (4) and V^0_{cp} according to Equation (3).

Altogether 214 tests (push-out tests and horizontally shear tests "in the field") were evaluated according to the aforementioned design proposal (Equation (5)) and compared with the evaluation results according to current design provisions in EN 1992-4. The database includes 66 single anchor tests, 54 tests on multiple-row anchorages of headed stud anchors and 94 tests on multiple-row anchorages with post-installed anchors (total = 214 tests). The full database is given in Appendix A.

Figure 3 shows the test-to-prediction ratio versus the embedment depth-to-anchor diameter ratio h_{ef}/d for the evaluated database according to the proposal and design provisions. Figure 3 shows a prediction comparison between the proposal and EN1992-4 provisions for 148 multiple-row anchorage tests and 66 single anchor tests. It clearly indicates that the proposed prediction equation correlates well with the test results and predicts the concrete pryout failure mode better than the current design provisions in EN1992-4. The proposed prediction for multiple-row anchorages (headed studs and PI anchors) with a mean test-to-prediction value of $\overline{x} = 0.96$ and coefficient of variation (C.O.V) of 25.9% indicate a clear improvement compared to the current design provision in EN 1992-4 with a mean value of $\overline{x} = 1.63$ and coefficient of variation (C.O.V) of 33.5%. Similar improvement is achieved for single anchor prediction (headed studs and PI anchors) with a mean test-to-prediction value of $\overline{x} = 1.04$ and coefficient of variation (C.O.V) of 9.7%, which is a significant improvement compared to the current design provision in EN 1992-4 with a mean value of $\overline{x} = 1.27$ and coefficient of variation (C.O.V) of 26.7%.

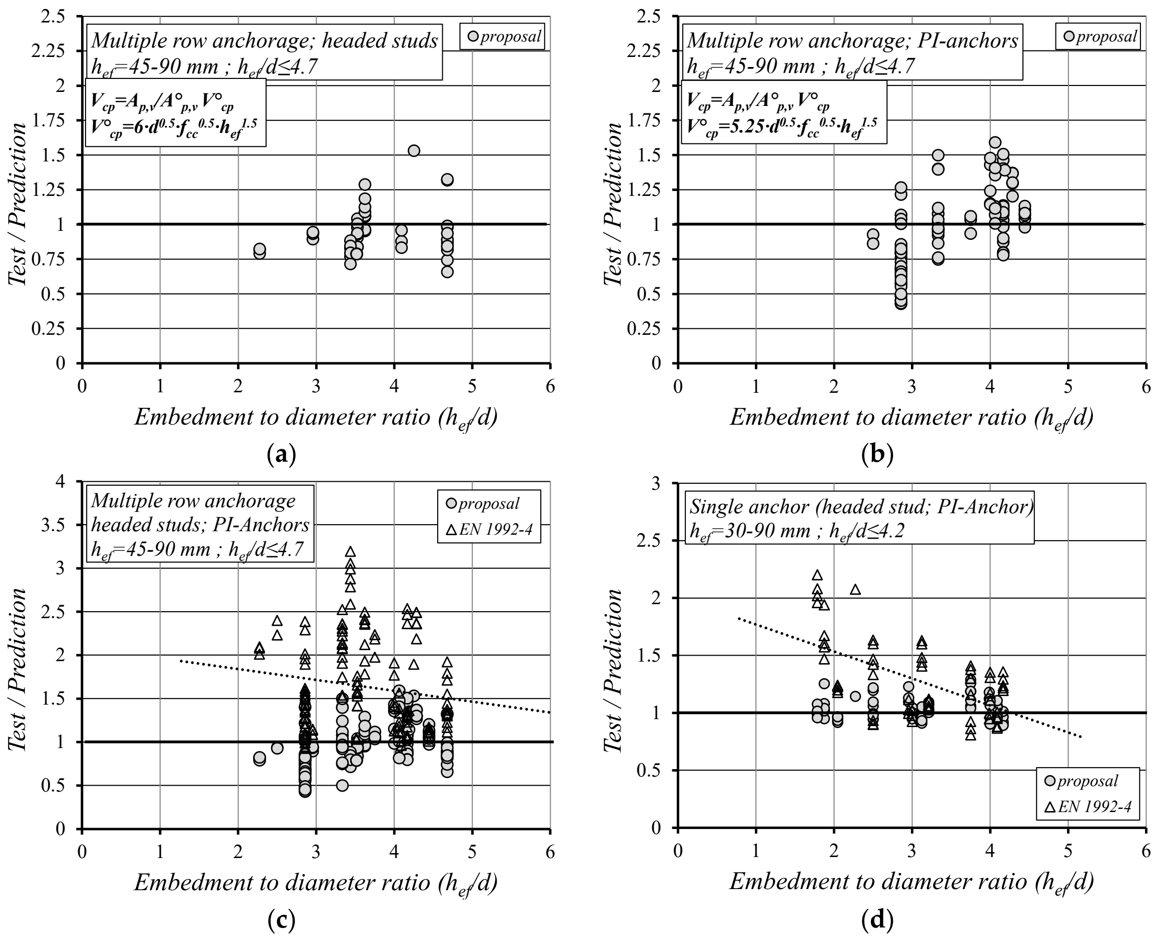


Figure 3. Test-to-predicted pryout capacity versus embedment depth ratio for group of anchors (**a**–**c**) and single anchor (**d**) comparing proposed average equation and current design formula from EN 1992-4.

4. Empirical Modification Factor for Multiple Rows

The following method to predict the pryout capacity of multiple-row anchorages is based on the basic pryout capacity equation for a single anchor (Equation (3)) and it proposes an easier and efficient handling in the practice. The concrete pryout capacity of available test results for multiple-row anchorages was reevaluated using the following proposed Equation (6):

$$V_{cp} = n \cdot V_{cp}^{0} \tag{6}$$

where n is the number of the studs in the connection and V_{cp}^{0} is the pryout capacity of single anchor according to Equation (3).

According to Figure 4a, the modification factor that accounts for the row spacing effect can be derived using a linear regression analysis for row spacing effects on the evaluated database. Based on the obtained results from the regression analysis, the following factors are proposed to account for the stud spacing effect:

$$\psi_{sp,cp}^{1} = 0.6 \cdot \left(S/h_{ef} \right)^{0.5} \tag{7a}$$

$$\psi_{sp,cp}^{2} = 0.3 \cdot (S/d)^{0.5} \tag{7b}$$

where S is the overall stud spacing parallel to the load direction.

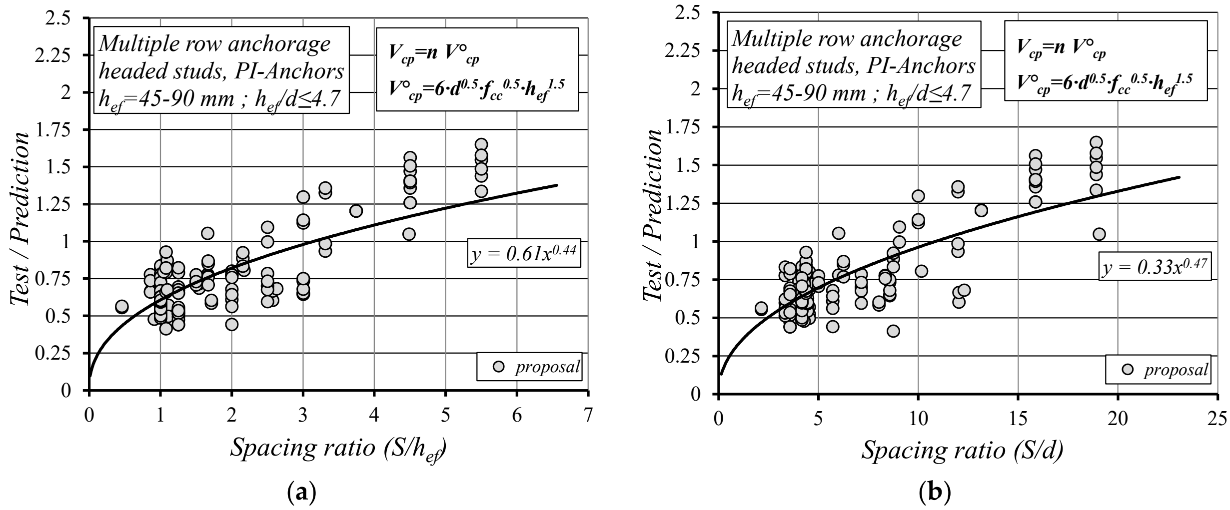


Figure 4. Modification factor for multiple-row anchor groups: (**a**) anchor spacing to embedment depth and (**b**) anchor spacing to anchor diameter.

For the sake of simplicity, the pryout capacity prediction is depicted against the spacing ratio including the major parameters, i.e., embedment depth h_{ef} and anchor diameter d.

An increase in the stud spacing perpendicular to the loading direction has only a moderate influence on the pryout capacity of an anchor group [15,16]. On the other hand, it was shown that the stud spacing parallel to the loading direction is the decisive factor for the pryout capacity which was explained by increasing the concrete resisting area and the internal lever arm between the resulting tensile pull-out force and compressive force in front of the anchor plate. Accordingly, it is recommended to apply a minimum stud spacing perpendicular to the load direction of Sy $\geq$ 6d that utilizes the full pryout capacity of the anchorage and prevents premature concrete pryout failure. Moreover, it is recommended to set the spacing ratio $\psi_{sp,cp} = 1$ for single-row anchorages perpendicular to the direction of loading. Note that current design requirements for concrete pryout prediction in EN 1992-4 do not specify anchor spacing limitations regarding concrete pryout failure mode.

However, ACI 318 provides a minimum anchor spacing perpendicular to the loading direction of Sy $\geq$ 4d. Whereas, EN 1994-1-1, design of composite steel and concrete structures, gives a minimum anchor spacing distance parallel to the loading direction of Sx ≥ 5d and perpendicular to the loading direction of Sy ≥ 2.5d and in the case of concrete-encased steel shapes Sy ≥ 4d.

Figure 5 presents the results of the evaluation of the available database using the basic Equation (2) modified by the stud spacing factors in Equation (7) and multiplied by the number of the studs in the connection:

$$V_{cp} = n \cdot V_{cp}^{0} \cdot \psi_{sp,cp} \tag{8}$$

where $\psi_{sp,cp}$ is the stud spacing factor (Equation (7)).

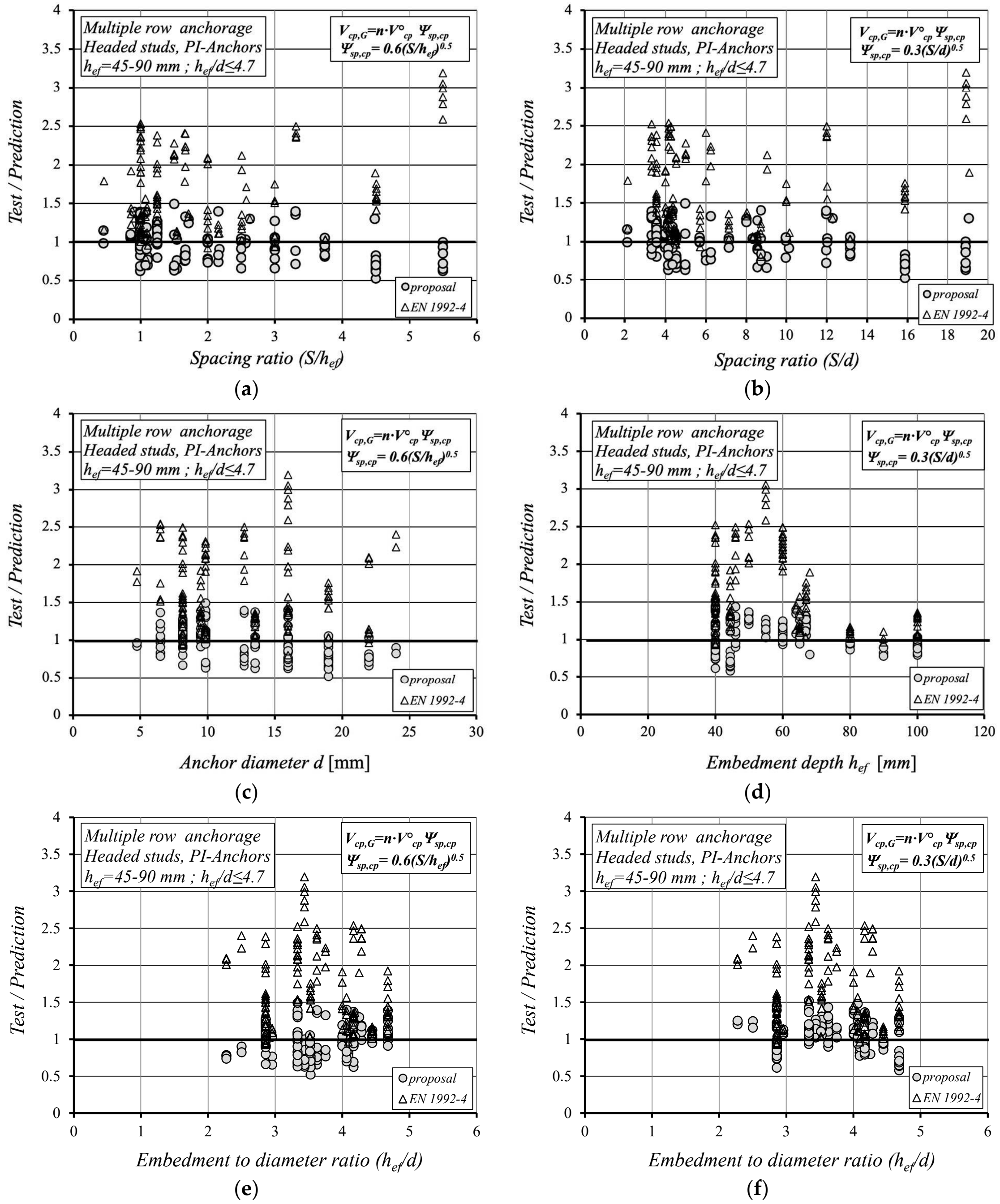


Figure 5. Modification factor for multiple-row anchor groups (headed studs and PI anchors) against (**a**) anchor spacing to embedment depth, (**b**) anchor spacing to diameter, (**c**) anchor diameter, (**d**) embedment depth and (**e**,**f**) embedment-to-diameter ratio.

Figure 5 confirms that the proposed prediction Equation (8) offers a significant improvement to the model given in EN1992-4 to estimate the pryout capacity of the anchorages. The mean test-to-prediction values of $\overline{x} = 0.99$ and $\overline{x} = 1.05$ and coefficient of variation (C.O.V) of 21% and 19%, respectively, clearly indicate an improvement compared to the current design provision in EN 1992-4, which has a mean value of $\overline{x} = 1.63$ and coefficient of variation (C.O.V) of 33.5%.

5. Proposed Prediction Methods Versus EN1992-4

The currently used design method for fastenings in concrete frequently underestimates the real concrete pryout capacity. One of the major reasons for the underestimation of concrete pryout capacity is the fact that the current methods do not account for the anchor diameter, which is found to have a significant influence on the pryout capacity of anchorages. Furthermore, the current prediction formula for fastenings loaded in shear and failing in pryout considers the pryout capacity simply as a multiple of the tension capacity of the anchorage, which may not be reasonable. The new prediction methods proposed here are based on an enhanced indirect-tension mechanical model which yields the basic average formula to predict the pryout capacity of a single anchor [8,16]. The proposed prediction formula (Equation (3)) takes into account the influence of anchor diameter and yields a more realistic evaluation of the concrete pryout resistance. The statistics of the proposed prediction equation for single-headed studs and post-installed anchors (PIAs) show a much better correlation with the test data versus those in EN 1992-4 (Table 2). Moreover, applying the simplified concrete breakout half-pyramid model for anchor groups using Equations (3)–(5) reveals a better prediction of the pryout capacity than the provisions in EN1992-4 (Table 2). The large scatter can be attributed to the different anchor systems and concrete compositions used in the tests (headed stud, undercut, expansion and bonded anchors). Note that the evaluated database includes push-off and pryout tests performed in different concrete compositions which failed partly in mixed mode (concrete and steel failure) and partly have large anchor spacing $S_x > 3h_{ef}$.

Table 2. Statistical evaluation for the proposed prediction methods and EN1992-4.

	Single Anchor		Group of Anchors							
	Proposed Equation (3)	EN1992-4 Equation (1)	Proposed Equation (5) (Half-Pyramid Model)		Proposed Equation (8) (Modification Factor ψ)				EN1992-4 Equation (1)	
					Headed Studs		PI Anchors			
	Headed Studs and PI Anchors		Headed Studs	PI Anchors	ψ^1 (Equation (7a))	ψ^2 (Equation (7b))	ψ^1 (Equation (7a))	ψ^2 (Equation (7b))	Headed Studs	PI Anchors
No. of tests	66		54	94	54		94		54	94
Mean	1.04	1.27	0.92	0.99	1.03	1.08	0.97	1.04	1.69	1.60
SD	0.10	0.34	0.17	0.28	0.18	0.20	0.22	0.20	0.62	0.51
COV (%)	9.7	27	18	29	17	18	23	20	37	32

The prediction method using an empirical modification factor to account for the stud spacing and the basic Equation (3) is easy to use and provides a good correlation with the test results for both headed studs and post-installed single anchors and anchor groups. For all cases, the mean ratio of test to prediction as well as the coefficient of variation provided by the new proposal clearly show a significant improvement than the current model in EN1992-4.

The design equations are derived based on the standard concept followed in the codes [2–5]. The determination of the concrete pryout design resistance ($V_{Rd,cp}$) is based on the characteristic concrete pryout resistance ($V_{Rk,cp}$) and the corresponding partial safety factor for the material which is here concrete (γ_{Mc}). The characteristic pryout resistance is defined as the 5%-fractile value of the mean pryout resistance ($V_{Rm,cp}$), which means that one can say with 90% confidence that 95% of the actual test strengths exceed the characteristic strength. Assuming a normal distribution of the evaluation result of the database is the 5%-fractile value statistically determined as $\gamma_{5\%} = \overline{x} - Ks$, where $\overline{x}$ is the mean value of tests, s is the standard deviation and K is a coefficient which depends on the number of tests [12]. Accordingly, one can assume a large experimental database (n = ∞, K = 1.645) with $\overline{x} = 1.04$ and s = 0.10 and COV of 9.65% (Table 2). Hence, the following characteristic concrete pryout resistance for a single anchor is derived:

$$V_{Rk,cp} = V_{Rm,cp}(1 - K \cdot V) \tag{9}$$

$$V_{Rk,cp} = k_{cp} \cdot d^{0.5} \cdot f_{cc}^{0.5} \cdot h_{ef}^{1.5} \tag{10}$$

where the 5%-fractile values are defined for uncracked and cracked concrete, assuming a cracking factor for headed studs ψ = 0.75 and for post-installed anchors ψ = 0.68 [18], in Table 3.

Table 3. 5%-fractile values.

	k_{cp}	
	Headed Studs	**PI Anchors**
Uncracked	5	4.5
Cracked	3.75	3

Thus, for the concrete pryout capacity design of anchorages, the following relation between design action and design resistance for all combinations of actions should be fulfilled:

$$V_{Sd} \le V_{Rd,cp} = V_{Rk,cp}/\gamma_{Mc} = \gamma_{5\%} V_{Rm,cp}/\gamma_{Mc} \tag{11}$$

where γ_{Mc} = 1.50 partial factor for concrete breakout failure mode, including pryout failure mode with the safety index of β = 4.2 [2]. Note that the safety concept used in this work follows the same principles as those used in the current codes and standards for the design of anchorages, which is based on 5%-fractile values and uses a safety factor. A more elaborate approach or a reliability analysis as given in [31,32] may be considered in future studies but are deemed out of the scope of this work.

Figure 6 shows that the prediction results of single and group of anchors (headed studs and post-installed anchors) using the new proposal follow a normal distribution. The marked differences in the mean value, standard deviation and the 5%-fractile values clearly show that the proposed prediction formulas result in a better correlation with the test database. The EN 1992-4-predicted 5%-fractile pryout resistance does not utilize the full capacity of a single anchor (Figure 6b). It utilizes about 82% of the available capacity of the anchorage which is economically inefficient. Note that the proposed prediction formula was derived based on an enhanced indirect-tension mechanical model for single-headed stud anchorage failed in pryout. The predicted 5%-fractile pryout resistance of anchor groups is in the same range for both EN 1992-4 and the proposed methods. However, the proposed methods (half-pyramid model and modification factors for anchor spacing) provide a realistic correlation with the test data.

As the pryout mechanism is based on the indirect tension model, it may be assumed that factors, which account for concrete cracking and reinforcement arrangement for anchors loaded in tension, are also valid for anchors loaded in shear and failing in pryout. However, further experimental and numerical investigations are required with regard to the influence of concrete edge distance, load eccentricity and verification of the aforementioned assumption.

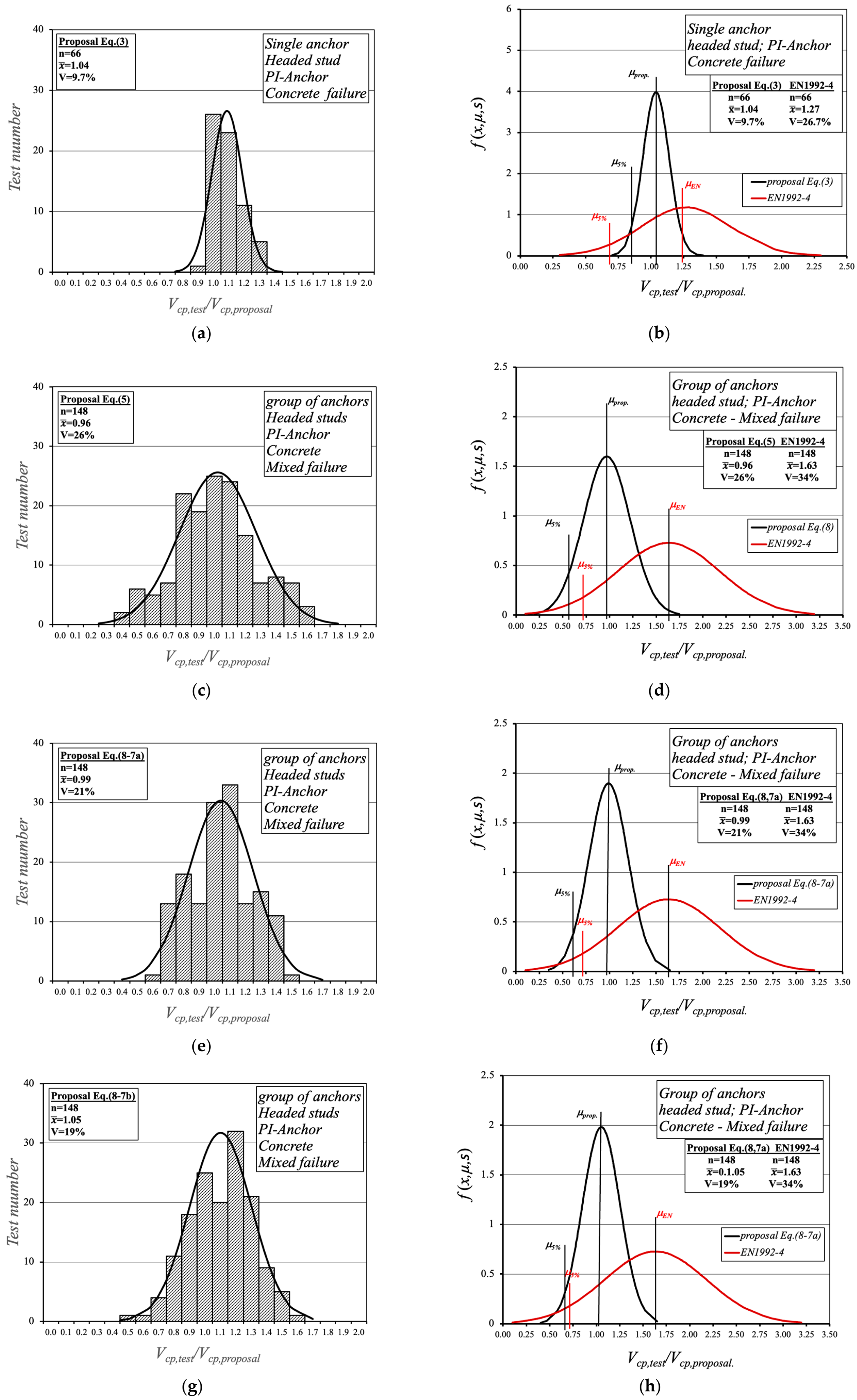


Figure 6. Statistical evaluation for a single and group of anchors (normal distribution), proposed prediction equations versus current prediction approach in EN 1992-4 for single anchor (**a**,**b**) and for group of anchors (**c**–**h**).

6. Conclusions

The current EN1992-4 design method for predicting pryout capacity of a single anchor and anchor groups for both headed studs and post-installed anchors is rather conservative and underestimates the pryout resistance. Although the EN1992-4 design method is based on the indirect-tension breakout mechanism, which realistically describes the concrete pryout mechanism, it does not appropriately predict the behavior. The EN1992-4 design method adopts the formula for predicting the concrete pull-out capacity which does not account for the influence of anchor diameter in the case of shear load. Moreover, the database includes limited inhomogeneous datasets regarding anchor type, concrete composition and test procedure which clearly indicate the need for further experimental investigation.

Based on the results of this study, the following conclusions can be drawn:

- The design procedures presented in this paper which are based on a modified indirect-tension breakout model for concrete pryout applying the latest reported prediction formula for a single anchor (Equation (3)) illustrate a good correlation with corresponding influencing parameters.
- The proposed Equation (6) according to the CCD method and Equation (8) using the modifying factors accounting for the stud spacing influence provide better predictors for the pryout capacity of a single anchor and anchor groups (headed stud and post-installed anchor configurations).
- The proposed prediction formulas for a single anchor and groups of anchors utilize the full anchor capacity and depict realistically the real behavior of headed stud and post-installed anchor configurations.
- These design recommendations to predict the pryout capacity of anchor groups are valid for shallowly embedded anchors (h_{ef}/d < 4.5) in normal-weight concrete (f_c < 50 MPa) away from edge and corner influence.
- The anchor spacing larger than 6d and smaller than 13.5d which corresponds to $S = 3h_{ef}$ implies the full pryout capacity of an anchor group.
- The pryout capacity of an anchor group increases proportionally to the square root of both the anchor spacing ($S^{0.5}$) and the anchor diameter ($d^{0.5}$).
- Further experimental and numerical investigations are needed to cover the edge and corner influence as well as the impact of high-strength concrete (f_c > 50 MPa) on the pryout capacity for both a single anchor and anchor group configuration.

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Data Availability Statement: Database supporting this research which collected and evaluated in Appendix A are available in corresponding publications listed in the references [12,14,16,19,21,28–30] and internal reports [23].

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Single anchor—evaluated available experimental tests, horizontally shear tests away from concrete edge influence "in the field".

Investigator	Test Number	Number of Studs	Failure Mode	Embed Depth	Stud Diameter	Concrete Strength	Stiffness Ratio	Anchor Spacing	Anchor Spacing	Peak Load	Proposed	Test/Calc. Proposed	EN 1992	Test/Calc. EN 1992
		n	(-)	h_{ef} (mm)	d (mm)	f_{cc} (N/mm^2)	h_{ef}/d	s_x (mm)	s_y (mm)	$V_{u,test}$ (kN)	$V_{u,cal,25}$ (kN)	$V_{u,test}/V_{u,cal}$	$V_{u,cal,25}$ (kN)	$V_{u,test}/V_{u,cal}$
Single Anchor														
Jebara [11]	KB30-8.1	1	cp	30.00	8.00	25.80	3.75	-	-	17.78	13.94	1.29	12.73	1.41
Jebara [11]	KB30-8.2	1	cp	30.00	8.00	25.80	3.75	-	-	16.39	13.94	1.19	12.73	1.30
Jebara [11]	KB30-8.3	1	cp	30.00	8.00	25.80	3.75	-	-	16.38	13.94	1.19	12.73	1.30
Jebara [11]	KB30-8.4	1	cp	30.00	8.00	25.80	3.75	-	-	17.37	13.94	1.26	12.73	1.38
Jebara [11]	KB30-8.5	1	cp	30.00	8.00	25.80	3.75	-	-	14.62	13.94	1.06	12.73	1.16
Jebara [11]	KB30-12.1	1	cp	30.00	12.00	25.80	2.50	-	-	20.20	17.08	1.19	12.73	1.60
Jebara [11]	KB30-12.2	1	cp	30.00	12.00	25.80	2.50	-	-	20.59	17.08	1.22	12.73	1.63
Jebara [11]	KB30-12.3	1	cp	30.00	12.00	25.80	2.50	-	-	17.91	17.08	1.06	12.73	1.42
Jebara [11]	KB30-12.4	1	cp	30.00	12.00	25.80	2.50	-	-	18.50	17.08	1.09	12.73	1.47
Jebara [11]	KB30-12.5	1	cp	30.00	12.00	25.80	2.50	-	-	16.80	17.08	0.99	12.73	1.33
Jebara [11]	KB30-16.1	1	cp	30.00	16.00	25.80	1.88	-	-	18.53	19.72	0.95	12.73	1.47
Jebara [11]	KB30-16.2	1	cp	30.00	16.00	25.80	1.88	-	-	21.09	19.72	1.08	12.73	1.67
Jebara [11]	KB30-16.3	1	cp	30.00	16.00	25.80	1.88	-	-	19.84	19.72	1.02	12.73	1.57
Jebara [11]	KB30-16.4	1	cp	30.00	16.00	25.80	1.88	-	-	24.47	19.72	1.25	12.73	1.94
Jebara [11]	KB30-16.5	1	cp	30.00	16.00	25.80	1.88	-	-	20.28	19.72	1.04	12.73	1.61
Jebara [11]	KB50-12.1	1	cp	50.00	12.00	25.80	4.17	-	-	32.99	36.74	0.91	27.40	1.22
Jebara [11]	KB50-12.2	1	cp	50.00	12.00	25.80	4.17	-	-	33.51	36.74	0.92	27.40	1.24
Jebara [11]	KB50-12.3	1	cp	50.00	12.00	25.80	4.17	-	-	35.08	36.74	0.96	27.40	1.29
Jebara [11]	KB50-12.4	1	cp	50.00	12.00	25.80	4.17	-	-	32.40	36.74	0.89	27.40	1.19
Jebara [11]	KB50-12.5	1	cp	50.00	12.00	25.80	4.17	-	-	36.84	36.74	1.01	27.40	1.36
Jebara [11]	KB50-16.1	1	cp	50.00	16.00	25.80	3.13	-	-	43.42	42.43	1.03	27.40	1.60
Jebara [11]	KB50-16.2	1	cp	50.00	16.00	25.80	3.13	-	-	44.18	42.43	1.05	27.40	1.63

Table A1. *Cont.*

Investigator	Test Number	Number of Studs	Failure Mode	Embed Depth	Stud Diameter	Concrete Strength	Stiffness Ratio	Anchor Spacing	Anchor Spacing	Peak Load	Proposed	Test/Calc. Proposed	EN 1992	Test/Calc. EN 1992
		n	(-)	h_{ef} (mm)	d (mm)	f_{cc} (N/mm^2)	h_{ef}/d	s_x (mm)	s_y (mm)	$V_{u,test}$ (kN)	$V_{u,cal,25}$ (kN)	$V_{u,test}/V_{u,cal}$	$V_{u,cal,25}$ (kN)	$V_{u,test}/V_{u,cal}$
Single Anchor														
Jebara [11]	KB50-16.3	1	cp	50.00	16.00	25.80	3.13	-	-	40.21	42.43	0.96	27.40	1.48
Jebara [11]	KB50-16.4	1	cp	50.00	16.00	25.80	3.13	-	-	38.17	42.43	0.91	27.40	1.41
Jebara [11]	KB50-16.5	1	cp	50.00	16.00	25.80	3.13	-	-	39.11	42.43	0.93	27.40	1.44
Jebara [11]	KB50-28.1	1	cp	50.00	28.00	25.80	1.79	-	-	54.80	56.12	0.99	27.40	2.02
Jebara [11]	KB50-28.2	1	cp	50.00	28.00	25.80	1.79	-	-	59.74	56.12	1.07	27.40	2.20
Jebara [11]	KB50-28.3	1	cp	50.00	28.00	25.80	1.79	-	-	56.42	56.12	1.02	27.40	2.08
Jebara [11]	KB50-28.4	1	cp	50.00	28.00	25.80	1.79	-	-	53.16	56.12	0.96	27.40	1.96
Jebara [11]	KB50-22.3	1	cp	90.00	22.00	25.80	4.09	-	-	115.43	120.14	0.97	132.34	0.88
Jebara [11]	KB50-22.4	1	cp	90.00	22.00	25.80	4.09	-	-	115.19	120.14	0.97	132.34	0.88
Jebara [11]	KB50-22.5	1	cp	90.00	22.00	25.80	4.09	-	-	113.60	120.14	0.95	132.34	0.87
Jebara [11]	KB50-28.1	1	cp	90.00	28.00	25.80	3.21	-	-	137.58	135.54	1.03	132.34	1.05
Jebara [11]	KB50-28.2	1	cp	90.00	28.00	25.80	3.21	-	-	143.98	135.54	1.07	132.34	1.10
Jebara [11]	KB50-28.3	1	cp	90.00	28.00	25.80	3.21	-	-	134.53	135.54	1.00	132.34	1.03
Jebara [11]	KB50-28.4	1	cp	90.00	28.00	25.80	3.21	-	-	138.80	135.54	1.03	132.34	1.06
Jebara [11]	KB50-28.5	1	cp	90.00	28.00	25.80	3.21	-	-	146.72	135.54	1.09	132.34	1.12
Jebara [11]	KB50-44.1	1	cp	90.00	44.00	25.80	2.05	-	-	160.78	169.91	0.96	132.34	1.23
Jebara [11]	KB50-44.2	1	cp	90.00	44.00	25.80	2.05	-	-	162.39	169.91	0.97	132.34	1.24
Jebara [11]	KB50-44.3	1	cp	90.00	44.00	25.80	2.05	-	-	154.13	169.91	0.92	132.34	1.18
Jebara [11]	KB50-44.4	1	cp	90.00	44.00	25.80	2.05	-	-	157.16	169.91	0.93	132.34	1.20
Jebara [11]	KB50-44.5	1	cp	90.00	44.00	25.80	2.05	-	-	162.31	169.91	0.96	132.34	1.24
Zhao [12]	3.1.1	1	cp	50.00	22.00	27.00	2.27	-	-	59.12	49.75	1.14	27.40	2.08
Zhao [12]	3.1.2	1	cp	65.00	22.00	27.00	2.95	-	-	83.95	73.74	1.10	81.23	0.99
Zhao [12]	3.1.3	1	cp	65.00	22.00	27.00	2.95	-	-	94.17	73.74	1.23	81.23	1.12
Zhao [12]	3.1.4	1	cp	65.00	22.00	27.00	2.95	-	-	86.62	73.74	1.13	81.23	1.03

Table A1. *Cont.*

Investigator	Test Number	Number of Studs n	Failure Mode (-)	Embed Depth h_{ef} (mm)	Stud Diameter d (mm)	Concrete Strength f_{cc} (N/mm^2)	Stiffness Ratio h_{ef}/d	Anchor Spacing s_x (mm)	Anchor Spacing s_y (mm)	Peak Load $V_{u,test}$ (kN)	Proposed $V_{u,cal,25}$ (kN)	Test/Calc. Proposed $V_{u,test}/V_{u,cal}$	EN 1992 $V_{u,cal,25}$ (kN)	Test/Calc. EN 1992 $V_{u,test}/V_{u,cal}$
Single Anchor														
Zhao [12]	3.1.5	1	cp	90.00	22.00	27.00	4.09	-	-	132.47	120.14	1.06	132.34	0.96
Zhao [12]	3.1.6	1	cp	90.00	22.00	27.00	4.09	-	-	130.68	120.14	1.05	132.34	0.95
Zhao [12]	3.1.7	1	cp	90.00	22.00	27.00	4.09	-	-	138.11	120.14	1.11	132.34	1.00
Zhao [12]	3.1.8	1	cp	115.00	22.00	27.00	5.23	-	-	163.71	173.53	0.94	191.15	0.86
Hawkins [13]	1S	1	cp	76.20	25.40	25.18	3.00	-	-	105.60	100.57	1.05	103.10	1.02
Hawkins [13]	3S	1	cp	76.20	25.40	23.75	3.00	-	-	98.20	100.57	1.00	103.10	0.98
Hawkins [13]	7S	1	cp	76.20	25.40	40.38	3.00	-	-	121.10	100.57	0.95	103.10	0.92
Hawkins [13]	11S	1	cp	76.20	19.10	24.94	3.99	-	-	102.70	87.21	1.18	103.10	1.00
Hawkins [13]	14S	1	cp	76.20	19.10	41.33	3.99	-	-	125.70	87.21	1.12	103.10	0.95
Eligehausen and Lehr [23]	13.1	1	cp	40.00	10.00	26.50	4.00	-	-	23.80	21.00	1.10	17.08	1.35
Eligehausen and Lehr [23]	13.2	1	cp	40.00	10.00	26.50	4.00	-	-	20.60	21.00	0.95	17.08	1.17
Eligehausen and Lehr [23]	13.3	1	cp	40.00	10.00	26.50	4.00	-	-	19.50	21.00	0.90	17.08	1.11
Eligehausen and Lehr [23]	13.4	1	cp	40.00	10.00	26.50	4.00	-	-	19.50	21.00	0.90	17.08	1.11
Eligehausen and Lehr [23]	13.5	1	cp	40.00	10.00	26.50	4.00	-	-	23.00	21.00	1.06	17.08	1.31
Grosser [16]	1	1	cp	60.00	16.00	25.00	3.75	-	-	50.71	48.80	1.04	62.74	0.81
Grosser [16]	2	1	cp	60.00	16.00	25.00	3.75	-	-	57.95	48.80	1.19	62.74	0.92
Grosser [16]	3	1	cp	60.00	16.00	25.00	3.75	-	-	54.05	48.80	1.11	62.74	0.86
Grosser [16]	4	1	cp	60.00	24.00	25.00	2.50	-	-	52.80	59.77	0.94	62.74	0.90
Grosser [16]	5	1	cp	60.00	24.00	25.00	2.50	-	-	56.56	59.77	0.95	62.74	0.90
Grosser [16]	6	1	cp	60.00	24.00	25.00	2.50	-	-	58.54	59.77	0.98	62.74	0.93

Table A2. Group of headed studs—evaluated available experimental tests, push-out and horizontally shear tests away from concrete edge influence "in the field".

Group of Anchors (Headed Studs)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^\circ$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm^2)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
Zhao [12]	3.2.1	4	cp	50.0	22.0	29.0	2.3	100.0	100.0	170.6	193.5	168.9	127.3	76.1
Zhao [12]	3.2.2	4	cp	50.0	22.0	29.0	2.3	100.0	100.0	164.7	193.5	168.9	127.3	76.1
Zhao [12]	3.2.3	4	cp	50.0	22.0	29.0	2.3	100.0	100.0	171.8	193.5	168.9	127.3	76.1
Zhao [12]	3.2.4	4	cp	65.0	22.0	29.0	3.0	100.1	100.0	217.9	226.1	219.6	188.8	186.0
Zhao [12]	3.2.5	4	cp	65.0	22.0	29.0	3.0	100.1	100.1	227.5	226.2	219.6	188.8	186.0
Zhao [12]	3.2.6	4	cp	65.0	22.0	29.0	3.0	100.1	100.1	230.1	226.2	219.6	188.8	186.0
Zhao [12]	3.2.7	4	cp	90.0	22.0	29.0	4.1	99.9	99.9	271.3	286.4	303.8	307.2	248.4
Zhao [12]	3.2.8	4	cp	90.0	22.0	29.0	4.1	99.9	99.9	295.6	286.4	303.8	307.2	248.4
Zhao [12]	3.2.9	4	cp	90.0	22.0	29.0	4.1	99.9	99.9	257.3	286.4	303.8	307.2	248.4
Anderson and Meinheit [15]	PO4F-6C	4	cp	46.0	12.7	48.5	3.6	76.4	76.4	145.0	109.1	103.1	98.1	58.3
Anderson and Meinheit [15]	PO4F-9A	4	cp	46.0	12.7	48.1	3.6	115.0	76.4	184.6	138.2	126.6	120.4	68.9
Anderson and Meinheit [15]	PO4F-9B	4	cp	46.0	12.7	48.0	3.6	115.0	76.4	202.4	138.2	126.6	120.4	68.9
Anderson and Meinheit [15]	PO4F-12B	4	cp	46.0	12.7	51.0	3.6	152.3	76.4	252.6	166.1	145.6	138.6	75.1
Anderson and Meinheit [15]	PO4F-6A	4	cp	46.0	12.7	48.0	3.6	76.4	76.4	194.8	109.1	103.1	98.1	58.3
Ollgaard [20]	A(1)	4	C	67.0	19.0	41.6	3.5	301.5	100.5	521.3	430.3	365.1	342.8	255.0
Ollgaard [20]	A(2)	4	C	67.0	19.0	41.6	3.5	301.5	100.5	578.2	430.3	365.1	342.8	255.0
Ollgaard [20]	A(3)	4	C	67.0	19.0	41.6	3.5	301.5	100.5	544.4	430.3	365.1	342.8	255.0
Ollgaard [20]	B(1)	4	C	67.0	19.0	39.1	3.5	301.5	100.5	487.5	430.3	365.1	342.8	255.0
Ollgaard [20]	B(2)	4	C	67.0	19.0	39.1	3.5	301.5	100.5	451.9	430.3	365.1	342.8	255.0

Table A2. *Cont.*

Group of Anchors (Headed Studs)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^{\circ}$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	**h_{ef} (mm)**	**d (mm)**	**f_{cc} (N/mm^2)**	**h_{ef}/d**	**s_x (mm)**	**s_y (mm)**	**$V_{u,test}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**
Ollgaard [20]	B(3)	4	C	67.0	19.0	39.1	3.5	301.5	100.5	451.9	430.3	365.1	342.8	255.0
Ollgaard [20]	LA(1)	4	C	67.0	19.0	29.7	3.5	301.5	100.5	435.9	430.3	365.1	342.8	255.0
Ollgaard [20]	LA(2)	4	C	67.0	19.0	29.7	3.5	301.5	100.5	471.5	430.3	365.1	342.8	255.0
Ollgaard [20]	LA(3)	4	C	67.0	19.0	29.7	3.5	301.5	100.5	439.5	430.3	365.1	342.8	255.0
Ollgaard [20]	SA(1)	4	C	55.0	16.0	32.8	3.4	302.5	99.0	346.9	365.5	275.5	255.4	101.2
Ollgaard [20]	SA(2)	4	C	55.0	16.0	32.8	3.4	302.5	99.0	370.1	365.5	275.5	255.4	101.2
Ollgaard [20]	SA(3)	4	C	55.0	16.0	32.8	3.4	302.5	99.0	354.1	365.5	275.5	255.4	101.2
Ollgaard [20]	SB(1)	4	C	55.0	16.0	33.0	3.4	302.5	99.0	323.8	365.5	275.5	255.4	101.2
Ollgaard [20]	SB(2)	4	C	55.0	16.0	33.0	3.4	302.5	99.0	300.7	365.5	275.5	255.4	101.2
Ollgaard [20]	SB(3)	4	C	55.0	16.0	33.0	3.4	302.5	99.0	334.5	365.5	275.5	255.4	101.2
Anderson [15]	PO4F-12B	4	M	46.0	12.7	51.0	3.6	152.3	76.4	258.9	166.1	145.6	138.6	75.1
Davies [25]	P44	4	M	44.5	9.5	45.2	4.7	114.3	0.0	89.0	74.4	105.5	114.1	42.7
Davies [25]	P53	4	M	44.5	9.5	43.2	4.7	38.2	38.1	96.1	55.4	61.0	65.9	38.0
Davies [25]	P54	4	M	44.5	9.5	43.2	4.7	114.3	0.0	96.1	74.4	105.5	114.1	42.7
Davies [25]	P83	4	M	44.5	9.5	30.8	4.7	20.3	38.1	67.6	46.0	44.4	48.1	34.0
An and Cederwall [31]	HSC11	4	M	66.8	19.0	102.3	3.5	250.0	150.0	695.7	436.3	331.5	310.8	332.6
An and Cederwall [31]	HSC12	4	M	66.8	19.0	96.5	3.5	250.0	150.0	675.7	436.3	331.5	310.8	332.6
An and Cederwall [31]	HSC21	4	M	66.8	19.0	96.5	3.5	250.0	150.0	675.7	436.3	331.5	310.8	332.6
An and Cederwall [31]	HSC1122	4	M	66.8	19.0	108.3	3.5	250.0	150.0	715.7	436.3	331.5	310.8	332.6

Table A2. *Cont.*

Group of Anchors (Headed Studs)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^\circ$**	**Proposed $V_{cp} = n \cdot V^\circ_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^\circ_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm^2)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
An and Cederwall [31]	NSC11	4	M	66.8	19.0	36.5	3.5	250.0	150.0	415.9	436.3	331.5	310.8	332.6
An and Cederwall [31]	NSC12	4	M	66.8	19.0	36.5	3.5	250.0	150.0	415.9	436.3	331.5	310.8	332.6
An and Cederwall [31]	NSC21	4	M	66.8	19.0	36.5	3.5	250.0	150.0	415.9	436.3	331.5	310.8	332.6
An and Cederwall [31]	NSC22	4	M	66.8	19.0	37.8	3.5	250.0	150.0	422.6	436.3	331.5	310.8	332.6
Davies [25]	P42	2	M	44.5	9.5	34.7	4.7	96.5	0.0	52.0	67.1	48.5	52.4	39.6
Davies [25]	P52	2	M	44.5	9.5	34.7	4.7	38.1	0.0	42.7	43.1	30.4	32.9	29.5
Davies [25]	P62	2	M	44.5	9.5	34.7	4.7	20.3	0.0	36.5	35.7	22.2	24.0	26.5
Davies [25]	P43	3	M	44.5	9.5	37.3	4.7	116.8	0.0	68.5	75.4	80.0	86.5	43.1
Davies [25]	P72	3	M	44.5	9.5	37.3	4.7	76.2	0.0	58.7	58.7	64.6	69.8	36.1
Davies [25]	P73	3	M	44.5	9.5	37.3	4.7	40.6	0.0	48.0	44.1	47.1	51.0	30.0
Davies [25]	P63	2	M	44.5	9.5	43.2	4.7	38.1	0.0	56.0	43.1	30.4	32.9	29.5
Davies [25]	P64	2	M	44.5	9.5	45.2	4.7	38.1	0.0	54.3	43.1	30.4	32.9	29.5
Davies [25]	P74	3	M	44.5	9.5	45.2	4.7	76.2	0.0	66.7	58.7	64.6	69.8	36.1
Anderson [15]	PO6F-6A	6	cp	46.0	12.7	51.0	3.6	152.3	76.4	267.3	166.1	218.5	207.9	79.0
Anderson [15]	PO6F-6B	6	cp	46.0	12.7	51.0	3.6	152.3	76.4	281.6	166.1	218.5	207.9	79.0
Jayas and Hosein [30]	JS-5	8	C	68.0	16.0	35.9	4.3	305.0	76.0	676.1	368.5	684.0	705.1	297.7

Table A3. Group of anchor bolts—evaluated available experimental tests, push-out and horizontally shear tests away from concrete edge influence "in the field".

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^\circ$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm^2)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
Eligehausen and Lehr [23]	HS-4x-H1-1	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	52.7	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-2	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	51.7	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-3	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	49.4	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-4	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	51.3	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-5	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	69.3	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-6	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	44.0	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-7	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	54.5	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-8	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	47.3	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-9	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	51.6	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-10	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	55.6	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-11	4	cp	40.0	8.2	25.2	2.9	50.0	50.0	44.1	64.5	66.7	56.3	34.3
Eligehausen and Lehr [23]	HS-4x-H1-12	4	cp	40.0	8.2	26.5	2.9	80.0	80.0	69.5	96.6	84.3	71.3	47.4
Eligehausen and Lehr [23]	HS-4x-H1-13	4	cp	40.0	8.2	26.5	2.9	80.0	80.0	62.3	96.6	84.3	71.3	47.4

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^\circ$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm²)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
Eligehausen and Lehr [23]	HS-4x-H1-14	4	cp	40.0	8.2	26.5	2.9	80.0	80.0	65.7	96.6	84.3	71.3	47.4
Eligehausen and Lehr [23]	HS-4x-H1-15	4	cp	40.0	8.2	26.5	2.9	80.0	80.0	45.3	96.6	84.3	71.3	47.4
Eligehausen and Lehr [23]	HS-4x-H1-16	4	cp	40.0	8.2	26.5	2.9	80.0	80.0	57.6	96.6	84.3	71.3	47.4
Eligehausen and Lehr [23]	HS-4x-H1-17	4	cp	40.0	8.2	26.5	2.9	100.0	100.0	71.7	121.5	94.3	79.7	57.4
Eligehausen and Lehr [23]	HS-4x-H1-18	4	cp	40.0	8.2	26.5	2.9	100.0	100.0	80.3	121.5	94.3	79.7	57.4
Eligehausen and Lehr [23]	HS-4x-H1-19	4	cp	40.0	8.2	26.5	2.9	100.0	100.0	69.2	121.5	94.3	79.7	57.4
Eligehausen and Lehr [23]	HS-4x-H1-20	4	cp	40.0	8.2	26.5	2.9	100.0	100.0	75.0	121.5	94.3	79.7	57.4
Eligehausen and Lehr [23]	HS-4x-H1-21	4	cp	40.0	8.2	26.5	2.9	100.0	100.0	61.0	121.5	94.3	79.7	57.4
Eligehausen and Lehr [23]	HS-4x-H1-22	4	cp	40.0	8.2	26.5	2.9	120.0	120.0	66.0	149.1	103.3	87.3	68.3
Eligehausen and Lehr [23]	HS-4x-H1-23	4	cp	40.0	8.2	26.5	2.9	120.0	120.0	75.1	149.1	103.3	87.3	68.3
Eligehausen and Lehr [23]	HS-4x-H1-24	4	cp	40.0	8.2	26.5	2.9	120.0	120.0	66.8	149.1	103.3	87.3	68.3
Lehr and Eligehausen [24]	HS-4x-H1-1	4	cp	40.0	8.2	26.5	2.9	120.0	120.0	69.6	149.1	103.3	87.3	68.3

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	Test Number	Number of Studs	Failure Mode	Embed Depth	Stud Diameter	Concrete Strength	Stiffness Ratio	Anchor Spacing	Anchor Spacing	Peak Load	Pyramid Model $\alpha = 35^\circ$	Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$	Proposed $V_{cp} = n \cdot V^\circ{}_{cp} \cdot \Psi_{sp,cp}(d)$	EN 1992-4
		n	(-)	h_{ef} (mm)	d (mm)	f_{cc} (N/mm^2)	h_{ef}/d	s_x (mm)	s_y (mm)	$V_{u,test}$ (kN)	$V_{u,cal,25}$ (kN)	$V_{u,cal,25}$ (kN)	$V_{u,cal,25}$ (kN)	$V_{u,cal,25}$ (kN)
Lehr and Eligehausen [24]	HS-4x-H1-2	4	cp	40.0	8.2	26.5	2.9	120.0	120.0	76.8	149.1	103.3	87.3	68.3
Lehr and Eligehausen [24]	HS-4x-H2-3	4	cp	60.0	9.9	26.9	3.3	60.0	60.0	128.6	115.0	124.2	113.4	55.8
Lehr and Eligehausen [24]	HS-4x-H2-4	4	cp	60.0	9.9	26.9	3.3	60.0	60.0	120.5	115.0	124.2	113.4	55.8
Lehr and Eligehausen [24]	HS-4x-H2-5	4	cp	60.0	9.9	26.9	3.3	60.0	60.0	110.2	115.0	124.2	113.4	55.8
Lehr and Eligehausen [24]	HS-4x-H2-6	4	cp	60.0	9.9	26.9	3.3	60.0	60.0	114.3	115.0	124.2	113.4	55.8
Lehr and Eligehausen [24]	HS-4x-H2-7	4	cp	60.0	9.9	26.9	3.3	60.0	60.0	133.5	115.0	124.2	113.4	55.8
Lehr and Eligehausen [24]	HS-4x-H28	4	cp	60.0	9.9	30.2	3.3	90.0	90.0	176.6	155.3	152.1	138.9	70.6
Lehr and Eligehausen [24]	HS-4x-H2-9	4	cp	60.0	9.9	30.2	3.3	90.0	90.0	164.7	155.3	152.1	138.9	70.6
Lehr and Eligehausen [24]	HS-4x-H2-10	4	cp	60.0	9.9	30.2	3.3	90.0	90.0	165.2	155.3	152.1	138.9	70.6
Lehr and Eligehausen [24]	HS-4x-H2-11	4	cp	60.0	9.9	30.2	3.3	90.0	90.0	161.0	155.3	152.1	138.9	70.6
Lehr and Eligehausen [24]	HS-4x-H2-12	4	cp	60.0	9.9	30.2	3.3	90.0	90.0	166.2	155.3	152.1	138.9	70.6
Lehr and Eligehausen [24]	Sp-4X-T-1	4	cp	80.0	9.9	27.1	4.4	80.0	80.0	191.9	177.1	191.3	201.6	171.7
Lehr and Eligehausen [24]	Sp-4X-T-2	4	cp	80.0	9.9	27.1	4.4	80.0	80.0	180.7	177.1	191.3	201.6	171.7

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^{\circ}$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm^2)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
Lehr and Eligehausen [24]	HS-4x-H3-1	4	cp	100.0	13.6	25.8	4.2	100.0	100.0	253.9	285.8	308.6	315.0	240.0
Lehr and Eligehausen [24]	HS-4x-H3-2	4	cp	100.0	13.6	25.8	4.2	100.0	100.0	261.8	285.8	308.6	315.0	240.0
Lehr and Eligehausen [24]	HS-4x-H3-3	4	cp	100.0	13.6	25.8	4.2	100.0	100.0	299.5	285.8	308.6	315.0	240.0
Lehr and Eligehausen [24]	HS-4x-H3-4	4	cp	100.0	13.6	25.8	4.2	100.0	100.0	330.4	285.8	308.6	315.0	240.0
Lehr and Eligehausen [24]	HS-4x-H3-5	4	cp	100.0	13.6	25.8	4.2	100.0	100.0	285.8	285.8	308.6	315.0	240.0
Lehr and Eligehausen [24]	Sp-4X-T-1	4	cp	40.0	4.8	33.6	4.0	40.0	40.0	62.3	46.7	50.4	50.4	30.4
Lehr and Eligehausen [24]	Sp-4X-T-2	4	cp	40.0	4.8	29.8	4.0	40.0	40.0	63.3	46.7	50.4	50.4	30.4
Lehr and Eligehausen [24]	HS-4x-H1-1	4	cp	40.0	6.5	29.4	3.3	40.0	40.0	77.7	51.1	55.2	50.4	30.4
Lehr and Eligehausen [24]	HS-4x-H1-2	4	cp	40.0	6.5	29.4	3.3	40.0	40.0	77.5	51.1	55.2	50.4	30.4
Lehr and Eligehausen [24]	HS-4x-H1-3	4	cp	40.0	6.5	29.4	3.3	40.0	40.0	83.1	51.1	55.2	50.4	30.4
Lehr and Eligehausen [24]	HS-4x-H1-4	4	cp	40.0	6.5	29.4	3.3	120.0	120.0	112.1	138.0	95.6	87.3	68.3
Lehr and Eligehausen [24]	HS-4x-H1-5	4	cp	40.0	6.5	29.4	3.3	120.0	120.0	114.0	138.0	95.6	87.3	68.3
Lehr and Eligehausen [24]	HS-4x-H1-6	4	cp	40.0	6.5	29.4	3.3	120.0	120.0	129.5	138.0	95.6	87.3	68.3

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^{\circ}$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	**h_{ef} (mm)**	**d (mm)**	**f_{cc} (N/mm^2)**	**h_{ef}/d**	**s_x (mm)**	**s_y (mm)**	**$V_{u,test}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**
Lehr and Eligehausen [24]	HS-4x-H1-7	4	cp	50.0	6.5	29.4	4.2	50.0	50.0	113.5	71.4	77.2	78.8	42.4
Lehr and Eligehausen [24]	HS-4x-H1-8	4	cp	50.0	6.5	29.4	4.2	50.0	50.0	116.7	71.4	77.2	78.8	42.4
Lehr and Eligehausen [24]	HS-4x-H1-9	4	cp	50.0	6.5	29.4	4.2	50.0	50.0	108.7	71.4	77.2	78.8	42.4
Upat-SM [25]	SM-4x-H2-1	4	cp	40.0	8.2	30.9	2.9	50.0	50.0	74.6	64.5	66.7	56.3	34.3
Upat-SM [25]	SM-4x-H2-2	4	cp	40.0	8.2	30.9	2.9	50.0	50.0	72.2	64.5	66.7	56.3	34.3
Upat-SM [25]	SM-4x-H2-3	4	cp	40.0	8.2	30.9	2.9	50.0	50.0	59.2	64.5	66.7	56.3	34.3
Upat-SM [25]	SM-4x-H2-4	4	cp	40.0	8.2	30.9	2.9	50.0	50.0	87.3	64.5	66.7	56.3	34.3
Upat-SM [25]	SM-4x-H2-5	4	cp	40.0	8.2	30.9	2.9	50.0	50.0	90.9	64.5	66.7	56.3	34.3
Fischer [26]	HS-4x-H1-6	4	cp	60.0	8.2	29.4	4.3	60.0	60.0	150.8	101.4	109.6	113.4	55.8
Fischer [26]	HS-4x-H1-7	4	cp	60.0	8.2	29.4	4.3	60.0	60.0	142.8	101.4	109.6	113.4	55.8
Fischer [26]	HS-4x-H1-8	4	cp	60.0	8.2	29.4	4.3	60.0	60.0	142.9	101.4	109.6	113.4	55.8
Fischer [27]	Sp-4X-T-9	4	cp	60.0	8.2	29.8	4.3	60.0	60.0	151.5	101.4	109.6	113.4	55.8
Fischer [27]	Sp-4X-T-10	4	cp	60.0	8.2	29.8	4.3	60.0	60.0	144.1	101.4	109.6	113.4	55.8

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model α = 35°**	**Proposed V_{cp} = $n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed V_{cp} = $n \cdot V^{\circ}{}_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	h_{ef} **(mm)**	d **(mm)**	f_{cc} **(N/mm²)**	h_{ef}/d	s_x **(mm)**	s_y **(mm)**	$V_{u,test}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**	$V_{u,cal,25}$ **(kN)**
Fischer [27]	Sp-4X-T-11	4	cp	60.0	8.2	29.8	4.3	60.0	60.0	133.3	101.4	109.6	113.4	55.8
Upat-PSZ [28]	Sp-4X-T-1	4	cp	80.0	9.9	30.0	4.4	80.0	80.0	214.4	177.1	191.3	201.6	171.7
Upat-PSZ [28]	Sp-4X-T-2	4	cp	80.0	9.9	30.0	4.4	80.0	80.0	219.8	177.1	191.3	201.6	171.7
Upat-PSZ [28]	Sp-4X-T-3	4	cp	80.0	9.9	30.0	4.4	80.0	80.0	207.1	177.1	191.3	201.6	171.7
Upat-PSZ [28]	Sp-4X-T-4	4	cp	80.0	9.9	30.0	4.4	80.0	80.0	209.9	177.1	191.3	201.6	171.7
Upat-PSZ [28]	Sp-4X-T-5	4	cp	100.0	13.6	26.5	4.2	100.0	100.0	316.4	285.8	308.6	315.0	240.0
Upat-PSZ [28]	Sp-4X-T-6	4	cp	100.0	13.6	28.3	4.2	100.0	100.0	334.4	285.8	308.6	315.0	240.0
Upat-PSZ [28]	Sp-4X-T-7	4	cp	100.0	13.6	26.5	4.2	100.0	100.0	325.8	285.8	308.6	315.0	240.0
Upat-PSZ [28]	Sp-4X-T-8	4	cp	100.0	13.6	26.5	4.2	100.0	100.0	332.3	285.8	308.6	315.0	240.0
Upat-PSZ [28]	Sp-4X-T-9	4	cp	100.0	13.6	28.3	4.2	100.0	100.0	330.8	285.8	308.6	315.0	240.0
Upat-PSZ [28]	Sp-4X-T-10	4	cp	100.0	13.6	28.3	4.2	200.0	200.0	425.6	500.1	436.5	445.5	375.0
Upat-PSZ [28]	Sp-4X-T-11	4	cp	100.0	13.6	28.3	4.2	200.0	200.0	424.1	500.1	436.5	445.5	375.0
Upat-PSZ [28]	Sp-4X-T-12	4	cp	100.0	13.6	28.3	4.2	200.0	200.0	414.9	500.1	436.5	445.5	375.0
Hofmann [14]	M16-FL-1	4	cp	130.0	16.0	28.4	8.1	140.0	70.0	274.5	315.4	387.6	552.4	320.7
Hofmann [14]	M16-FL-2	4	cp	65.0	16.0	28.5	4.1	70.0	70.0	155.1	128.5	137.0	138.1	130.7
Hofmann [14]	M16-FL-3	4	cp	65.0	16.0	28.5	4.1	70.0	70.0	186.0	128.5	137.0	138.1	130.7
Hofmann [14]	M16-FL-4	4	cp	64.0	16.0	22.3	4.0	70.0	70.0	137.0	126.9	134.9	134.9	128.7
Hofmann [14]	M16-FL-5	4	cp	67.0	16.0	27.3	4.2	70.0	70.0	191.3	131.7	141.3	144.5	134.6
Hofmann [14]	M16-FL-6	4	cp	64.0	16.0	27.3	4.0	70.0	70.0	189.5	126.9	134.9	134.9	128.7

Table A3. *Cont.*

Group of Anchors (Anchor Bolt)														
Investigator	**Test Number**	**Number of Studs**	**Failure Mode**	**Embed Depth**	**Stud Diameter**	**Concrete Strength**	**Stiffness Ratio**	**Anchor Spacing**	**Anchor Spacing**	**Peak Load**	**Pyramid Model $\alpha = 35^\circ$**	**Proposed $V_{cp} = n \cdot V^\circ_{cp} \cdot \Psi_{sp,cp}(h_{ef})$**	**Proposed $V_{cp} = n \cdot V^\circ_{cp} \cdot \Psi_{sp,cp}(d)$**	**EN 1992-4**
		n	**(-)**	**h_{ef} (mm)**	**d (mm)**	**f_{cc} (N/mm^2)**	**h_{ef}/d**	**s_x (mm)**	**s_y (mm)**	**$V_{u,test}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**	**$V_{u,cal,25}$ (kN)**
Hofmann [14]	M16-FL-7	4	cp	64.0	16.0	22.3	4.0	70.0	70.0	177.0	126.9	134.9	134.9	128.7
Hofmann [14]	M16-FL-8	4	cp	65.0	16.0	22.3	4.1	70.0	70.0	170.6	128.5	137.0	138.1	130.7
Hofmann [14]	M16-FL-9	4	cp	65.0	16.0	22.3	4.1	70.0	70.0	192.9	128.5	137.0	138.1	130.7
Hofmann [14]	M16-FL-10	6	cp	65.0	16.0	27.3	4.1	140.0	70.0	203.7	182.2	290.7	195.3	165.2
Hofmann [14]	M16-FL-11	6	cp	65.0	16.0	27.3	4.1	140.0	70.0	191.6	182.2	290.7	195.3	165.2
Hofmann [14]	M16-FL-12	6	cp	65.0	16.0	27.3	4.1	140.0	70.0	212.2	182.2	290.7	195.3	165.2
Grosser [15]	M16-Fl-1	4	cp	60.0	16.0	25.0	3.8	100.0	100.0	166.0	160.3	151.2	146.4	75.9
Grosser [15]	M16-Fl-2	4	cp	60.0	16.0	25.0	3.8	100.0	100.0	169.7	160.3	151.2	146.4	75.9
Grosser [15]	M16-Fl-3	4	cp	60.0	16.0	25.0	3.8	100.0	100.0	150.0	160.3	151.2	146.4	75.9
Grosser [15]	M24-Fl-4	4	cp	60.0	24.0	26.0	2.5	100.0	100.0	185.8	196.3	185.2	146.4	75.9
Grosser [15]	M24-Fl-5	4	cp	60.0	24.0	25.0	2.5	100.0	100.0	169.4	196.3	185.2	146.4	75.9

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