BEHAVIOR AND DESIGN OF FASTENINGS WITH HEADED STUDS WITH SUPPLEMENTARY REINFORCEMENT CLOSE TO AN EDGE UNDER SHEAR LOADS PERPENDICULAR TO THE EDGE

TRAGVERHALTEN UND BEMESSUNG VON BEFESTIGUNGEN MIT KOPFBOLZEN MIT RÜCKHÄNGEBEWEHRUNG AM BAUTEILRAND UNTER QUERLASTEN SENKRECHT ZUM RAND

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SUMMARY

EN 1992-4 [1] regulates the design of fastenings in concrete. It contains provisions for fastenings at an edge with supplementary reinforcement to take up shear forces perpendicular to the edge. The model given in [1] is very conservative. Therefore tests were performed at the University of Stuttgart to investigate the behavior of fastenings with up to four rows of headed studs perpendicular to the edge with supplementary reinforcement consisting of stirrups and edge reinforcement under a shear load perpendicular to the edge. The test results were used to develop an improved design model for such fastenings.

ZUSAMMENFASSUNG

EN 1992-4 regelt die Bemessung von Befestigungen in Beton. Die Norm enthält Vorschriften für Befestigungen mit Rückhängebewehrung zur Aufnahme einer Querlast senkrecht zum Rand. Das in [1] angegebene Bemessungsmodell ist sehr konservativ. Daher wurden an der Universität Stuttgart Versuche mit Befestigungen mit bis zu vier Kopfbolzenreihen senkrecht zum Rand und einer aus Bügel und Randbewehrung bestehenden Rückhängebewehrung unter einer Querlast senkrecht zum Rand durchgeführt. Aus den Versuchsergebnissen wurde ein verbessertes Bemessungsmodell für diese Befestigungen abgeleitet.

KEYWORDS: Fastenings, heads studs, shear load, concrete edge failure, supplementary reinforcement, shear tests, analytical model

1. INTRODUCTION

EN 1992-4 "Design of fastenings for use in concrete" [1] was published in 2018. The provisions in [1] assume for the verification of fastenings at the edge of a concrete member loaded by a shear load perpendicular to the edge, that the failure crack starts from the anchors closest to the edge and stirrups as supplementary reinforcement are anchored in the assumed failure body with an anchorage length according to Eurocode 2 [2] for tension bars. Both assumptions are very conservative for fastenings without hole clearance (e.g. headed studs welded to a baseplate) [3, 4].

This paper deals with the influence of supplementary reinforcement consisting of stirrups and straight edge bars on the behavior of fastenings with up to four rows of headed studs perpendicular to an edge loaded by a shear load perpendicular to the edge. First the design model given in [1] is explained. Then the tests performed at the Institut für Werkstoffe im Bauwesen, Universität Stuttgart, are described and the main test results are presented. After comparing the results with the predictions according to the model in [1], an improved model is proposed for fastenings at an edge without and with supplementary reinforcement.

2. MODEL GIVEN IN EN 1992-4

According to EN 1992-4 [1], the failure load of anchorages with supplementary reinforcement in the form of stirrups or straight bars with $d_{s,re} \leq 16$ mm and edge reinforcement can be obtained on the basis of the strut-and-tie model shown in Figure 1. Bars are assumed as effective only if their distance from the fastener is $\leq 0{,}75 c_1$ (c_1 = edge distance). Furthermore, the anchorage length l_1 of the supplementary reinforcement in the concrete breakout body must be at least equal to 10 $d_{s,re}$ (straight bars) or 4 $d_{s,re}$ (bars with hook, bend or loop).

According to the model in [1] the mean resistance $V_{Rm,re}$ of the supplementary reinforcement of one fastener is given by:

$$V_{Rm,re} = \sum_n V^0_{Rm,re} \tag{1}$$

$$V^0_{Rm,re} = \frac{l_1 \cdot \pi \cdot d_{s,re} \cdot f_{bm} / (\alpha_1 \cdot \alpha_2)}{x} \leq \frac{f_{ym} A_{s,re}}{x} \tag{2}$$

where n is the number of effective legs of the supplementary reinforcement; f_{bm} is the mean bond strength (f_{bm} = 1,33 x 1,5 f_{bd} = 2,0 f_{bd}); f_{bd} is the design bond strength according to EN 1992-1-1 [2]; f_{ym} is the mean yield strength of the rebar; $A_{s,re}$ is the area of one leg; α_1 is an influencing factor equal to 0,7 for hooked bars if $c_d \geq 3d_{s,re}$ or 1,0 if $c_d < 3d_{s,re}$ and for straight bars [2]; α_2 is a factor according to [2] to consider the influence of cover on bond strength; x is a factor to consider the ratio lever arm between reinforcement and applied shear load and internal lever arm (compare Fig. 1)

$$x = (1+e_s/z) \quad (3)$$

where e_s is the distance between reinforcement and shear force acting on a fixture; z is the internal lever arm of the concrete member that is approximately equal to 0,85d with d = min (depth of concrete member; $2h_{ef}$; $2c_1$).

The failure load of an anchorage with supplementary reinforcement is given as

$$V_{Rm} = max(V_{Rm,c}; V_{Rm,re}) \quad (4)$$

with $V_{Rm,c}$ = mean failure load of a fastening for concrete edge breakout calculated according to the model in [1] which is based on [5].

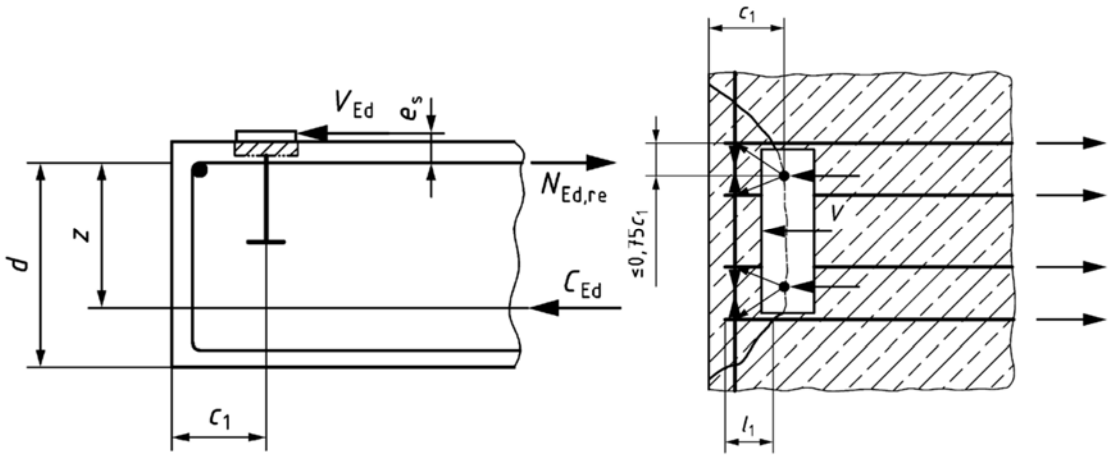


Fig. 1: Strut-and-tie model according to [1] for fastenings with supplementary reinforcement loaded by a shear load perpendicular to the edge

3. TESTS AND TEST RESULTS

Four different anchor groups with 22 mm headed studs welded to a 25 mm thick baseplate were tested: groups 1 x 2, 2 x 2, 2 x 4 and 4 x 2, where a x b denotes a group with “a” anchor rows perpendicular to the edge and “b” anchors in a row. The spacing of the anchors in both directions was 150 mm. The embedment depth was h_{ef} = 190 mm [6] or h_{ef} = 155 mm [7]. During casting the anchor plates were located at the bottom side of a 500 mm thick test member. The ribbed supplementary reinforcement ($f_{ym} \approx$ 550 MPa) consisted of stirrups (spacing a = 200 mm) and straight edge bars with the same diameter. The stirrups enclosed the edge bars. The concrete compressions strength measured on cubes with 150 mm side length varied between 21 MPa and 31 MPa. Varied was the edge distance of the anchors closest to the edge (c_1 = 85 mm [6] or 120 mm [7]), the diameter of the supplementary reinforcement ($d_{s,re}$ = 12 mm, 16 mm, 16 mm + 14 mm (bundled bars [6] or 20 mm [7]) and the restraint of baseplate uplift. To measure the force taken up by stirrups, in each test series the stirrups of at least one test were equipped with electrical strain gauges placed such that they were crossed by the expected failure crack. For comparison tests in unreinforced concrete were performed. The total number of tests was about 60.

Fig. 2 shows the test setup. To minimize friction a 2 mm thick Teflon sheet was placed between concrete surface and loading plate. While in [6] uplift of the baseplate was restrained by a cross beam, in [7] uplift of the base plate was not restrained. The distance between the support reactions and the applied shear load was large enough to allow the formation of an unrestricted concrete edge breakout body. The tests were performed in uncracked concrete. The shear load was increased in steps under deformation control.

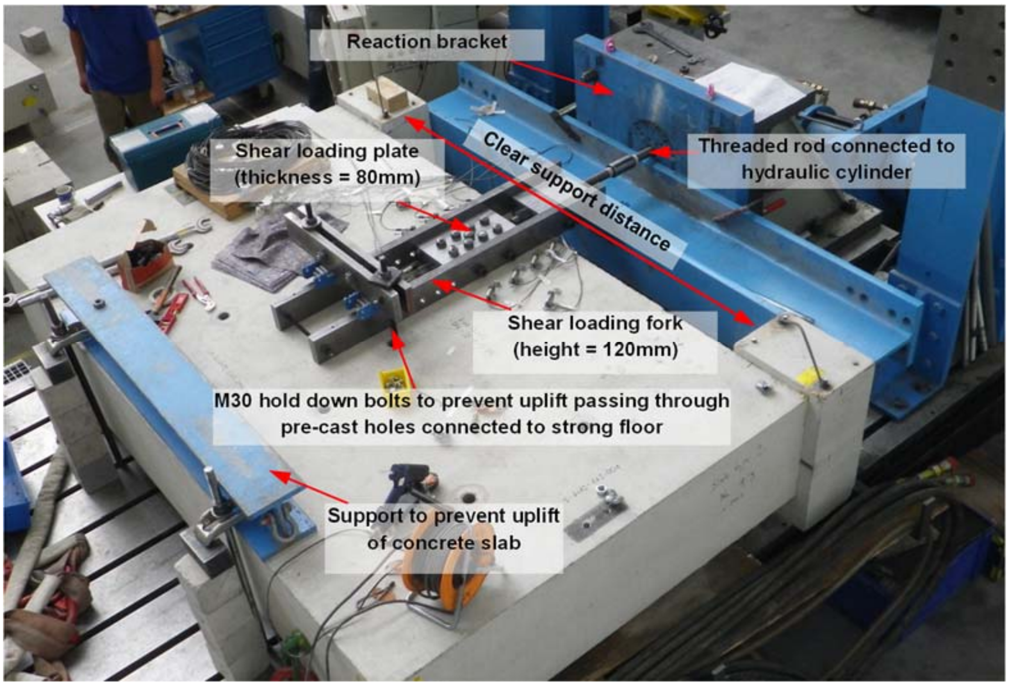


Fig. 2: Typical test setup used for the tests [6]

In tests in unreinforced concrete edge breakout was observed. The failure crack started from the back anchors. This agrees with [4]. In tests with supplementary reinforcement, the shear failure load was significantly higher than in tests in plain concrete and the load-displacement behavior became much more ductile (Fig. 3). While in tests with stirrups $d_{s,re}$ = 12 mm and 16 mm the stirrups yielded, in tests with stirrups $d_{s,re}$ = 16 mm + 14 mm (bundled bars) failure of the struts that formed between the headed studs and the anchorage of the stirrups was observed. This failure mode limits the shear failure load. In Fig. 4 the shear force applied to the fastening, the shear force taken up by stirrups (calculated from the measured steel strains) and the shear force taken up by concrete (difference between applied shear force and value taken up by stirrups) are plotted as a function of the shear displacements. In the test shown in Fig. 4a) uplift of the baseplate was restrained, while in the test of Fig. 4b) baseplate uplift was not restrained. The stirrups became activated at a load approximately equal to the failure load of the fastening in unreinforced concrete. If baseplate uplift was restrained the shear load taken up by concrete did not decrease much with increasing applied shear displacement, because the restraint caused a compression force on the concrete breakout body resulting in increased friction in the failure crack. If uplift of the baseplate was not restrained, the shear load taken up by the concrete decreased with increasing shear displacement. At peak load it amounted to about 50% of the failure load of the fastening in unreinforced concrete. In Fig. 5 the tension force taken up by stirrups $d_{s,re}$ =12 mm of group 4 x 2 are plotted as a function of the shear displacements. First the stirrups 4 and 5 directly besides the fastening were activated. After yielding of these stirrups, stirrups 3 and 5 in the next row and then stirrups 2 and 5 were activated up to the yield force. The outer most stirrups 1 and 8 did not reach the yield stress because their anchorage in the breakout body was too short.

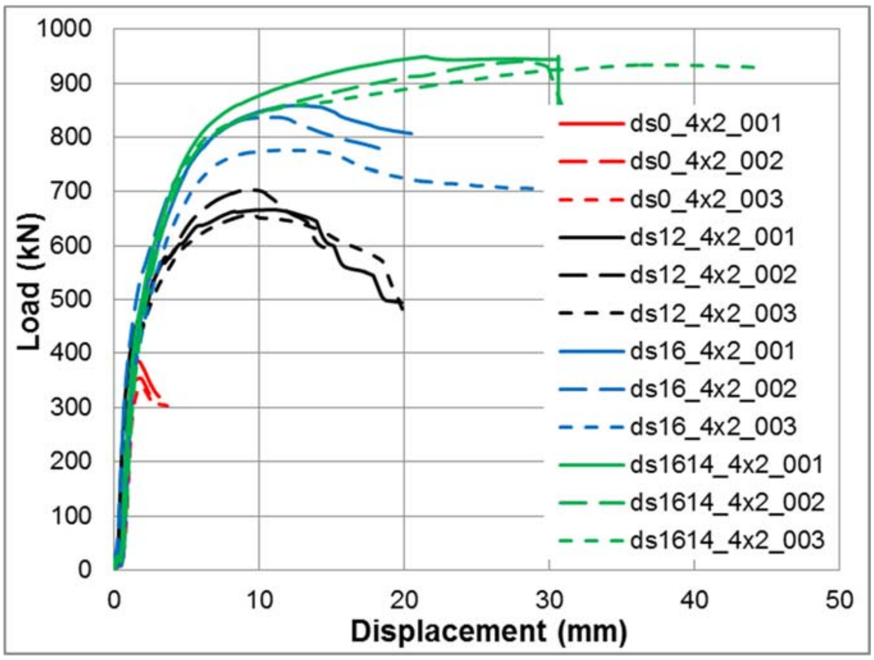
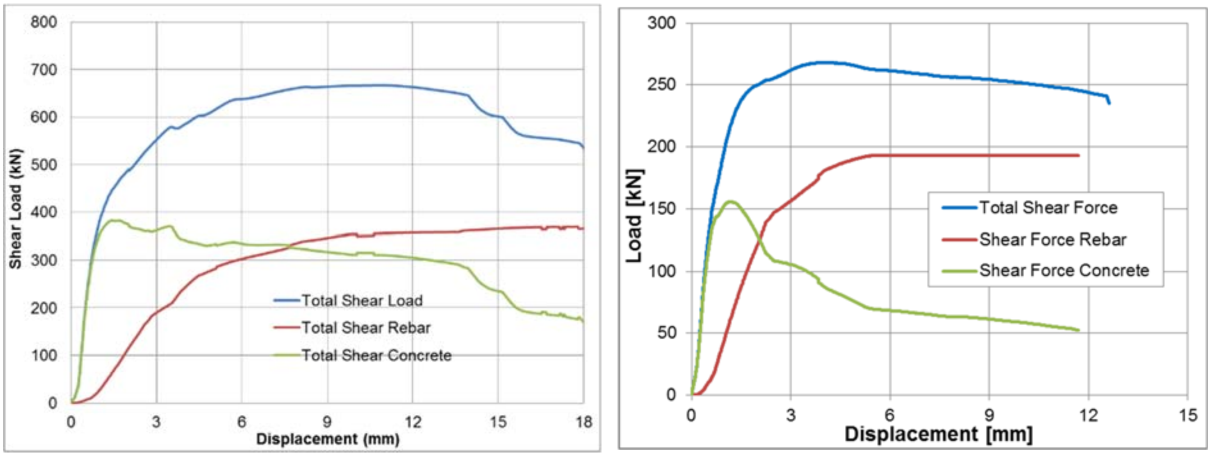


Fig. 3: Load displacement curves obtained for groups 4 x 2 [6]



a) *b)*

Fig. 4: Applied shear force (blue line), shear load taken up by stirrups (red line) and by concrete (green line) as a function of shear displacement of baseplate. a) Test with group 4 x 2 [8], b) tests with group 2 x 2 [7]

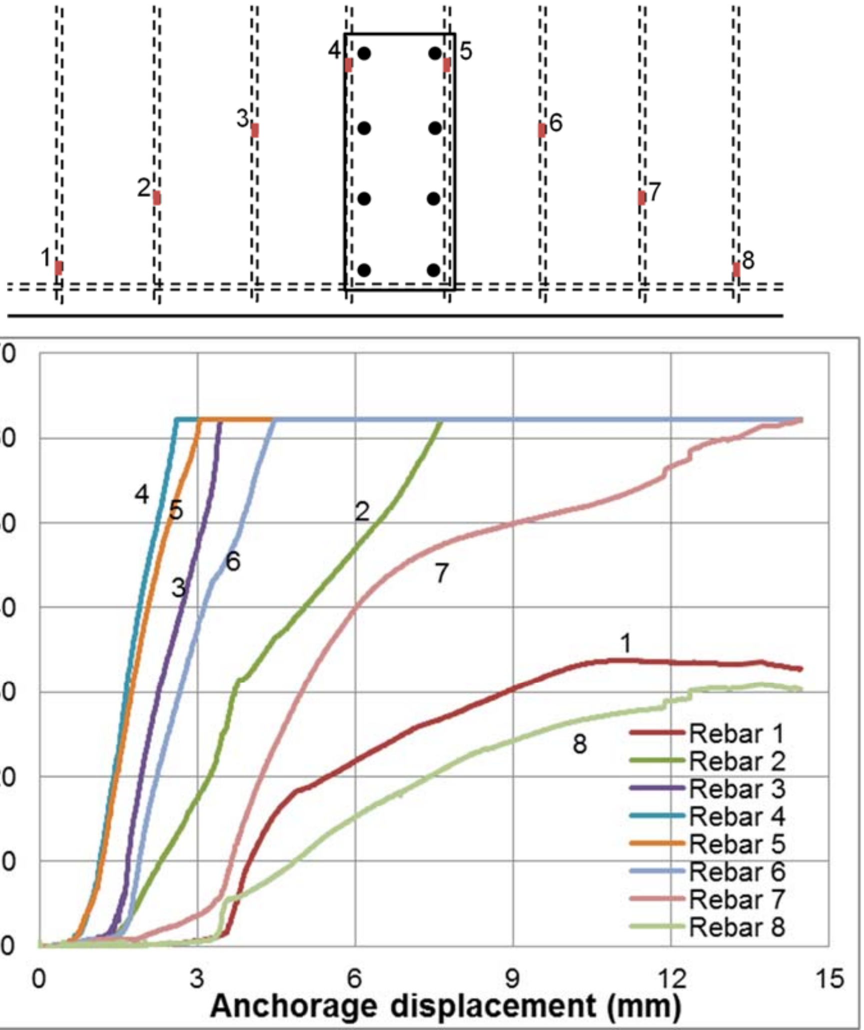


Fig. 5: Tension force carried by individual stirrups as a function of shear displacement of baseplate. Test on group 4 x 2 [8]

4. COMPARISON OF TEST RESULTS WITH PREDICTIONS ACCORDING TO EN 1992-4

In EN 1992-4 [1] it is assumed, that the failure crack starts from the anchor closest to the edge. Therefore the failure loads of the shear tests with groups 1 x 2, 2 x 2 and 4 x 2 in unreinforced concrete members predicted according to [1] are constant. In reality, the failure crack occurs at the back anchor row and the measured mean failure loads of groups 2 x 2 and 4 x 2 are about 2,8-times and 7,8 times higher respectively than the value valid for groups 1 x 2.

Fig. 6 shows the mean failure loads of the different tests series with supplementary reinforcement normalized to the mean failure load of the same tests in unreinforced concrete as a function of the cross section of one stirrup leg. In addition, the prediction according to [1] is shown as well. On average the mean failure loads of groups 1 x 2, 2 x 2 and 4 x 2 increase by a factor of about 2,5, while the failure loads of groups 2 x 4 increases by a factor of 4,3. In contrast to the test results, EN 1992-4 predicts no increase of the failure load with increasing stirrup cross section, because the calculated resistance of the reinforcement is lower than the concrete resistance. This is due to the fact that only the bent of the stirrup is located in the assumed breakout body and the calculated tension load taken up by the hook is very small.

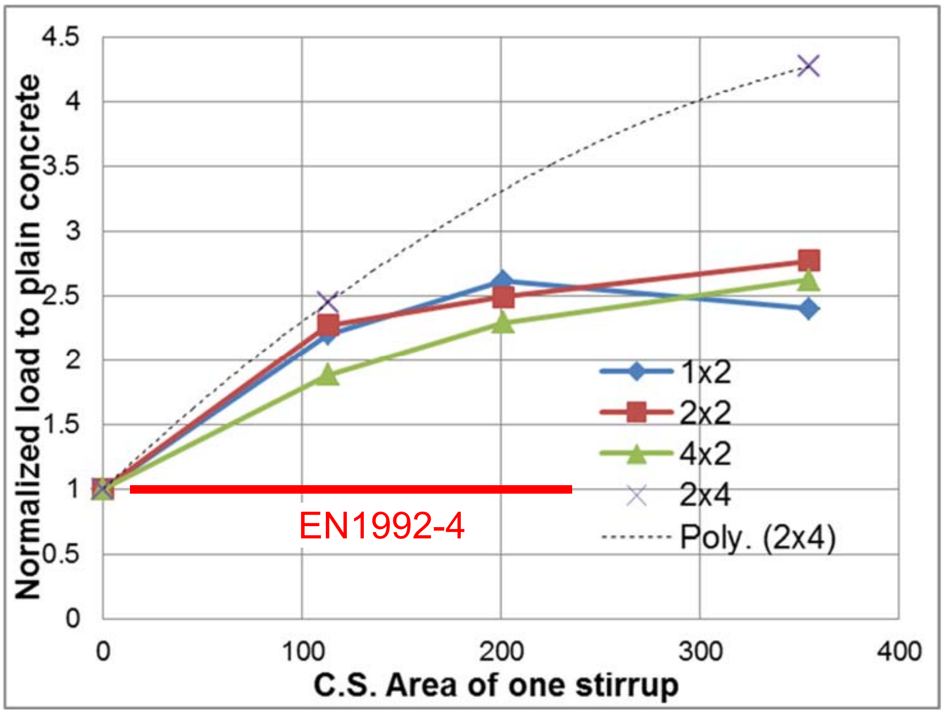


Fig. 6: Mean failure loads of tests with supplementary reinforcement normalized to mean failure load in unreinforced concrete as a function of cross section of one stirrup leg [6]

5. PROPOSED NEW MODEL

To better predict the measured failure loads, a new model has been developed [8, 9] based on the model by Schmid [3]. He performed tests with single anchors or anchor rows. The stirrups did not yield and strut failure was not observed. Therefore Schmid assumes in his model, that only the stirrups directly beside or between anchors are highly effective, while other stirrups are much less effective. He neglects strut failure but limits the model to stirrups with $d_{s,re} \leq 16$ mm.

The following mayor modifications are proposed in the Schmid [3] model:

a) The failure crack is assumed from the back row of anchors, b) the value of the effectiveness factor, ψ_I for the ith stirrup, used in the Schmid model (see Eq. (5.4)) depends on yielding/non yielding of the (i-l)th stirrup previously intercepted by the crack, c) the total failure load for an anchorage amounts to the contribution of reinforcement and the contribution of concrete, d) the failure load is limited by strut failure.

The mean edge failure load V_{um} of a fastening with supplementary reinforcement is calculated according to Eq. (5).

$$V_{um} = k_1 \times V_{um,c} + V_{um,re} \leq V_{um,st} \quad (5)$$
$$\geq V_{um,c}$$

k_1	=	Factor to take into account restraint of baseplate uplift
	=	0,5, if uplift of baseplate is not restrained (general case)
	=	1,0, if uplift of baseplate is restrained (e.g. by a sufficiently large compression force or by structural means)
$V_{um,c}$	=	mean failure load of the fastening without supplementary reinforcement calculated according to [5] assuming that the failure crack occurs at the back anchor or anchors
$V_{um,re}$	=	$N_{um,re}/(1+e_s/z)$ (5.1)
e_s, z	=	see Eq. (3)
$N_{um,re}$	=	mean tension force taken up by stirrups
	=	$\sum_n N^0_{um,re}$ (5.2)
n	=	number of effective stirrups. Effective are stirrups with an anchorage length in the assumed breakout body (see Fig. 1) $l_1 \geq 4d_{s,re}$ ($d_{s,re} \leq 16$ mm) or $l_1 \geq 5{,}5\, d_{s,re}$ ($d_{s,re} > 16$ mm)

$N^{0}_{um,re}$	=	mean tension force taken up by one stirrup	
	=	$N^{0}_{um,hook} + N^{0}_{um,bond} \leq A_{s,re} \cdot f_{ym}$	(5.3)
$N^{0}_{um,hook}$	=	$\psi_1 \cdot \psi_2 \cdot \psi_3 \cdot A_s \cdot f_{ym} \cdot \left(\frac{f_{cm,cube}}{30} \right)^{0,1}$	(5.4)
ψ_1	=	effectiveness factor	
	=	0,95 for stirrups between or directly beside anchors and for stirrups further away from anchors, if the tension force taken up by the stirrup closer to the anchor calculated according to Eq. (5.3) is equal to the yield force	
	=	0,16 for all other stirrups intercepted by the assumed crack	
ψ_2	=	influence of ratio diameter of edge bar $d_{s,l}$ to diameter of stir-rup	
	=	$\left(d_{s,l} / d_{s,re} \right)^{2/3} \leq 1,2$	(5.5)
ψ_3	=	influence of ratio anchorage length l_1 to edge distance c_1 (see Fig. 1) and diameter of stirrup	
	=	$(l_1/c_1)^{0,4} \cdot (10/d_{s,re})^{0,25}$	(5.6)
$N^{0}_{um,re,bond}$	=	$\pi \cdot d_{s,re} \cdot l_1' \cdot f_{bm} / \alpha_2$	(5.7)
f_{bm}, α_2	=	see Eq. (2)	
l_1'	=	$l_1 - \min l_1$, $\min l_1$ see Eq. (5.2)	(5.8)

To calculate the failure load in case of strut failure, the model proposed by Berger [10] for fastenings with supplementary reinforcement under tension load was adopted for shear loading [9]. This is possible because of the similarities of the load transfer mechanism under tension and shear load (compare Fig. 7a) with Fig. 7b)). One gets for the fastening shown in Fig. 7b)

$V_{um,st}$	=	$V_{um,c} \cdot \psi_{st,V}$	(5.9)
$\psi_{st,V}$	=	$\psi^{0}_{st,V} = 2,75 - 1,17 \cdot x/c_1$	(5.10)
x	=	distance between headed stud and stirrup	

For the tested groups 2 x 2 with stirrups beside the anchors (Fig. 8) the factor $\psi_{st,v}$ is calculated as follows:

$\psi_{st,V}$	=	$\psi^{0}_{st,V}(x_1) \cdot A_{c,V1}/A_{c,V} + A_{c,V2}/A_{c,V} + \psi^{0}_{st,V}(x_2) \cdot A_{c,V3}/A_{c,V}$	(5.11)
$\psi^{0}_{st,V}(x_i)$	=	factors according to Eq. (5.10) for the distances x_1 and x_2	

$A_{c,V}$ = projected area calculated according to [1]

$A_{c,V,i}$ = partial areas of $A_{c,V}$, see Fig. 8

Because of $A_{c,V1} = A_{c,V2}$ and $x_1 = x_2$ one gets

$$\psi_{st,V} = (\psi^0_{st,V}(x_1) \cdot 3c_1+s)/(3c_1+s) \quad (5.12)$$

For other fastenings the calculation of the factor $\psi_{st,V}$ is described in [9].

In Fig. 9 the ratios mean measured failure loads to calculated mean values are plotted as a function of the cross-section of one stirrup leg. The figure shows, that the predictions are conservative, also for fastenings without supplementary reinforcement. If neglecting the limitation for strut failure, the failure loads of the fastenings with the largest stirrup cross-section are overestimated significantly [9]. Therefore this limitation is needed. The failure loads predicted for the group 2 x 4 (4 anchors parallel to the edge) is much lower than the measured values, because the proposed model does not take into account the number of compression struts.

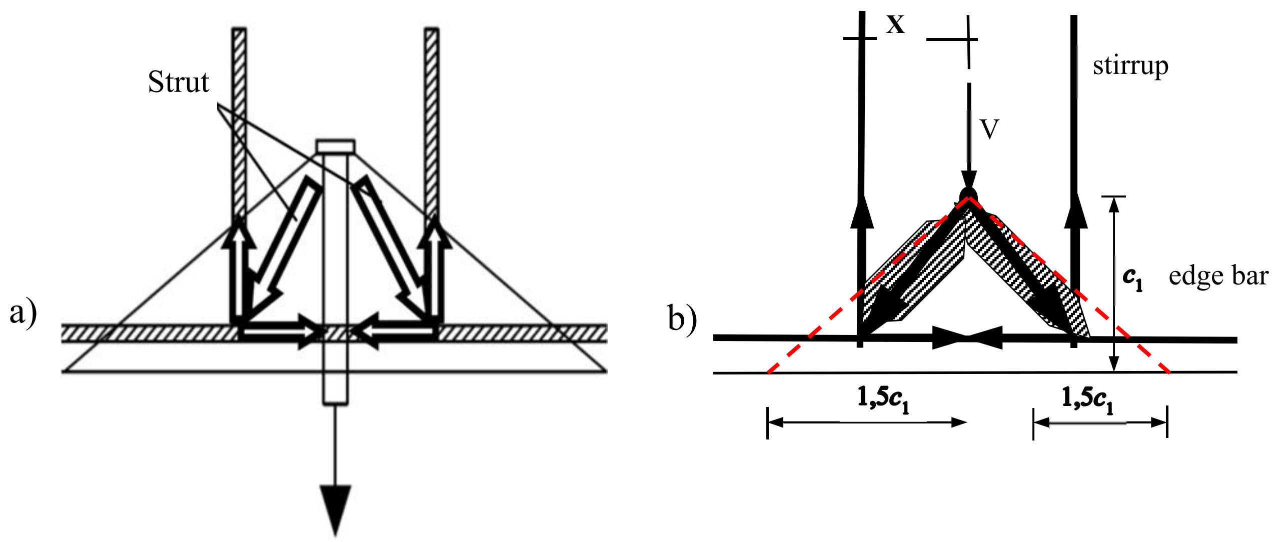


Fig. 7: Strut-and-tie models for fastenings with supplementary reinforcement, a) tension loading, b) shear loading, taken from [9]

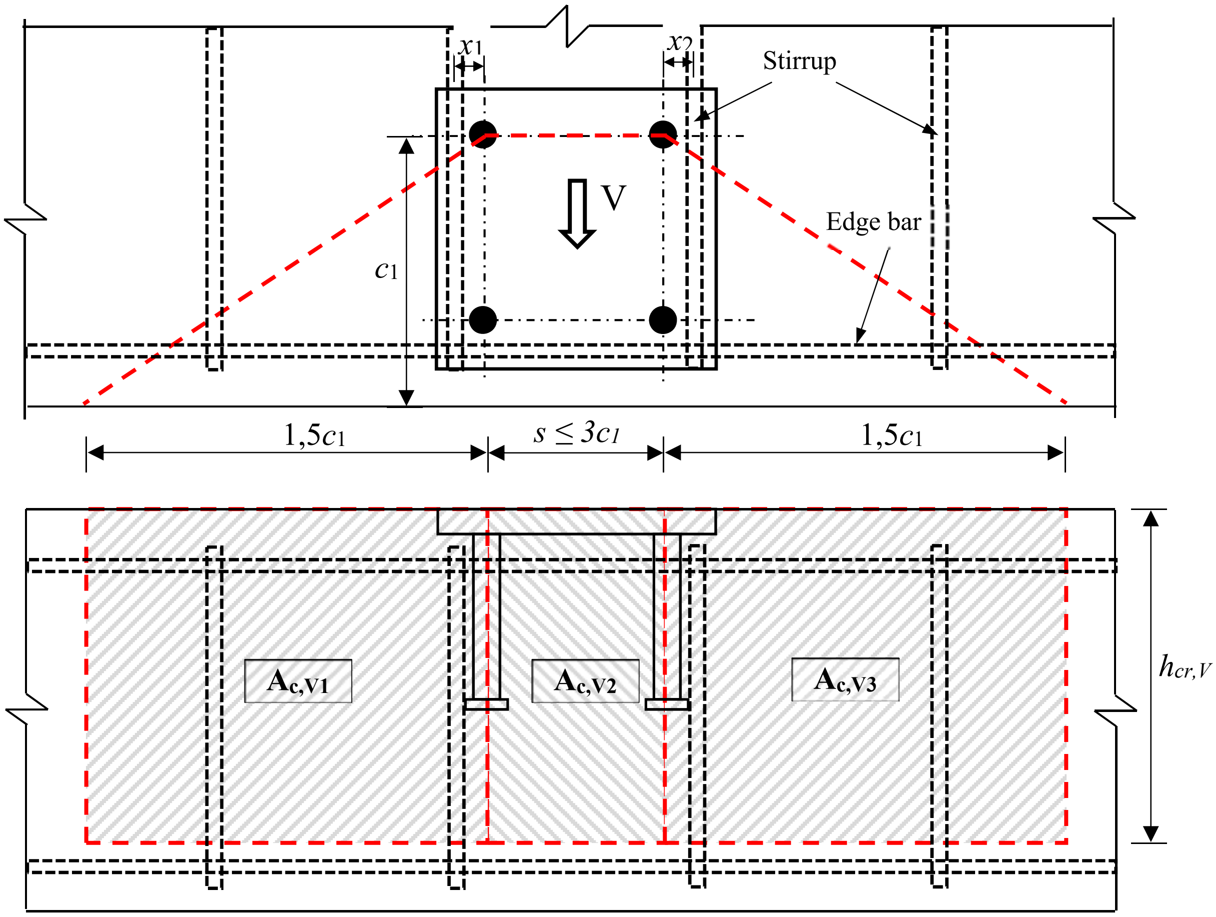


Fig. 8: Group with 2 x 2 headed studs at the edge of a concrete member with stirrups beside the anchors, taken from [9]

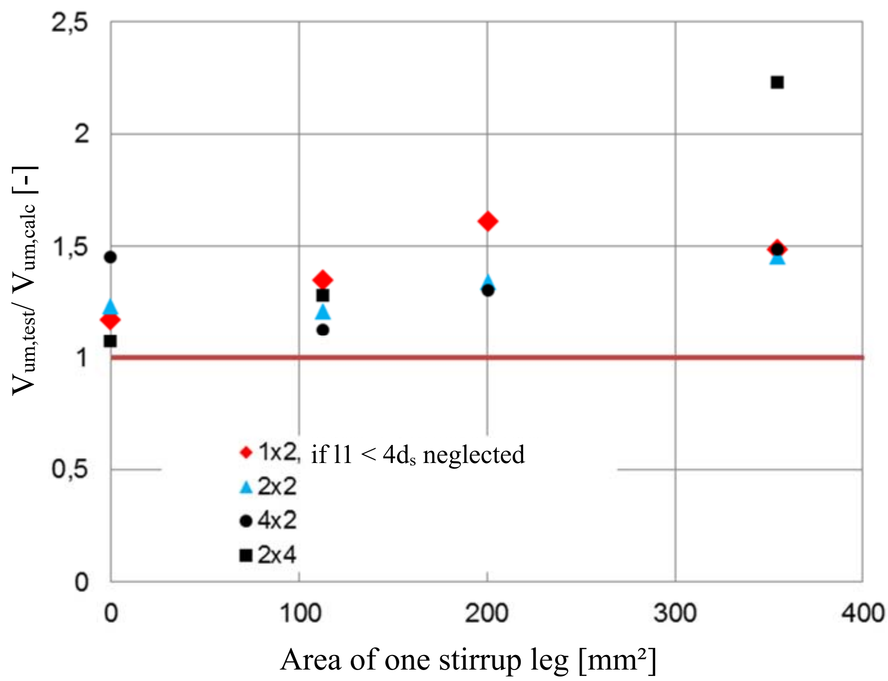


Fig. 9: Ratios mean measured failure loads to calculated values as a function of cross section of one stirrup leg, [9]

Assuming $F_{u,5\%}/F_{u,m} = 0{,}75$ the design resistance for concrete edge failure is obtained according to Eq. (6) [9]

$$V_{Rd} = k_1 \cdot V_{Rd,c} + V_{Rd,re} \leq V_{Rd,st} \qquad (6)$$
$$\geq V_{Rd,c}$$

k_1 = see Eq. (5)

$V_{Rd,c}$ = value calculated according to [1] assuming that the failure crack occurs at the back anchor(s)

$$V_{Rd,re} = N_{Rd,re}/(1+e_s/z) \qquad (6.1)$$

$$N_{Rd,re} = \sum_n N^0_{Rd,re} \qquad (6.2)$$

e_s, z, n = see Eq. (5.1) and Eq. (5.2)

$$N^0_{Rd,re} = N^0_{Rd,hook} + N^0_{Rd,bond} \leq A_{s,re} \cdot f_{yd} \qquad (6.3)$$

$$N^0_{Rd,hook} = 0{,}75 \cdot N^0_{um,hook}/\gamma_{M,c} \qquad (6.4)$$

$$N^0_{Rd,bond} = 0{,}75 \cdot N^0_{um,bond}/\gamma_{Mc} \qquad (6.5)$$

f_{yd} = f_{yk}/γ_{Ms}

f_{yk} = nominal yield strength of stirrup

γ_{Ms} = 1,15

γ_{Mc} = 1,5

$V_{rd,st}$ = $\psi_{st,V} \cdot V_{Rd,c}$

$\psi_{st,V}$ = see Eq. (5.10) or Eq. (5.12) respectively

6. SUMMARY

The failure load of fastenings at an edge of the concrete member loaded by a shear load towards the edge is increased significantly by supplementary reinforcement. The behavior can be described by a strut-and-tie model. If concrete edge failure is caused by yielding or failure of the anchorage of the stirrup in the breakout body, the failure load increases with increasing cross-section of the stirrups. However, the increase of the failure load is limited by failure of the struts forming between headed studs and the anchorage of the stirrups.

The model in EN 1992-4 [1] is rather conservative (see Section 4). The model given in [3] predicts well the failure loads of fastenings with one row of anchors parallel to the edge if the stirrups do not yield. However, in practice fastenings with more than one anchor row perpendicular to the edge are used. Therefore, tests were performed to investigate the behavior of such fastenings [6, 7]. Based on the test results (see Section 3) a new model is proposed [8, 9], which is an extension of the model given in [3] and takes into account the phenomena observed in the tests (see Section 5). The proposed model predicts the measured failure loads conservatively but in general with sufficient accuracy for applications in practice. However, several open questions should be solved by additional research (see [8, 9]).

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