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Experimental and numerical investigations on the concrete edge failure of anchor groups of arbitrary configurations

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Experimental and numerical investigations on the concrete edge failure of anchor groups of arbitrary configurations

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Abstract. Concrete edge failure often governs the failure of anchorages, which are installed close to the concrete edge and are loaded in shear perpendicular towards the edge. The design provisions for concrete edge failure given in the current codes are rather limited in applicability. Only anchorages arranged in a rectangular pattern are allowed. For anchorages without hole clearance, the maximum permissible anchor pattern is with three anchors in a row, and for anchorages with hole clearance, a maximum of only two anchors in a row is allowed. Furthermore, for anchor groups with multiple anchor rows loaded in shear perpendicular to the edge, the failure load may be calculated by assuming the failure crack initiating from the front anchor row (EN1992-4) or by assuming the failure crack initiating from the back anchor row (fib Bulletin 58, ACI 318). No design guidelines exist for non-rectangular anchor configurations. In such cases, the design is based on engineering judgement. In this study, experimental and numerical investigations were performed on anchor groups of triangular and hexagonal configurations to study the concrete edge failure. It was observed that the failure crack always initiates from the back anchor row, even in case of anchor groups, where the first cracking is associated with the first anchor row. The first cracking may have an influence on the displacement behaviour of the group, which might limit the design in SLS. However, this is dependent on the displacement behaviour of individual anchors within the group, edge distance, spacing and hole clearance.

1. Introduction

Anchorages loaded in shear might fail by steel failure, concrete edge failure, pryout failure or pullout failure. Which failure mode will govern the design is depending on a number of parameters such as anchor type and size, steel grade, anchor embedment depth, concrete strength, edge distance, anchor configuration, loading direction (Eligehausen et al. 2006 [1]). For anchorages placed close to the concrete edge and loaded in shear perpendicular and towards the edge, the failure is often governed by concrete edge breakout failure. The design provisions for concrete edge failure given in the current codes and guidelines such as EN1992-4 [2], fib Bulletin 58 [3] and ACI 318 [4] are rather limited in applicability. Only anchorages arranged in a rectangular pattern are allowed according to EN1992-4 and fib Bulletin 58. For anchorages without hole clearance, the maximum permissible anchor pattern is with three anchors in a row, and for anchorages with hole clearance, a maximum of only two anchors in a row is allowed. Figure 1 depicts the permissible anchor configurations according to EN1992-4.
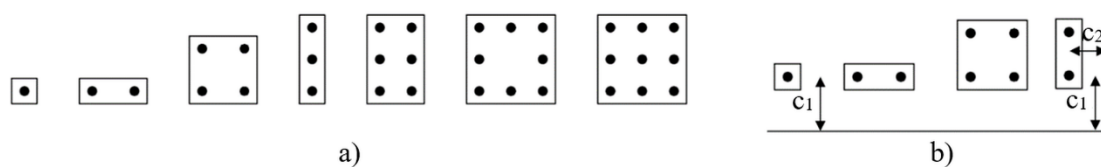
Figure 1. Permissible configurations according to EN1992-4: a) fastenings without hole clearance for all edge distances and fastenings with hole clearance situated far from edges ($c_i \geq \max\{10h_{ef}; 60d_{nom}\}$) for all load directions and fastenings with hole clearance situated near to an edge ($c_i < \max\{10h_{ef}; 60d_{nom}\}$) loaded in tension only; b) fastenings with hole clearance situated near to an edge ($c_i < \max\{10h_{ef}; 60d_{nom}\}$) for all load directions.

In reality, the shear load distribution within anchor groups and the failure mechanism of shear loaded anchor groups close to the concrete edge loaded perpendicular to the edge are very complex and are dependent on parameters and combination of parameters such as edge distance, anchor spacing, hole clearance. In many cases, it is not obvious whether a redistribution of the shear load to the back anchor row after crack formation at the front anchor row can take place. Therefore, according to the current design recommendations and guidelines, it is often assumed that failure crack for concrete edge failure appears from the front anchor row. This approach can be very conservative for anchorages with multiple anchor rows (see also in Grosser 2012 [5], Sharma et al., 2017 [6]).
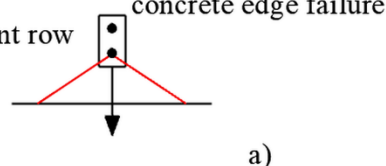
For anchor groups with multiple anchor rows close to an edge loaded in shear perpendicular to the edge, the failure load may be calculated by assuming the failure crack initiating from the front anchor row (EN1992-4) or by assuming the failure crack initiating from the front or back anchor row (fib Bulletin 58, ACI 318) as the examples in figure 2 show. However, if the crack initiation for concrete edge failure mode is considered from the back anchor row, then for the verification for steel failure, only anchors, which are not in the failure breakout body can be considered to resist shear loads (figure 2b)).

Furthermore, due to functional and architectural requirements, non-rectangular anchor configurations and anchorages with more than three anchor rows also find their application. Since no design guidelines exist for such cases, the design is based on engineering judgement.

The aim of this study was to experimentally and numerically investigate the concrete edge failure of anchor groups of triangular and hexagonal configurations, which are not covered by current standards.
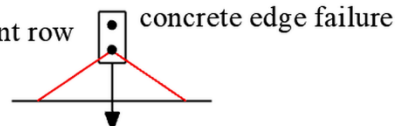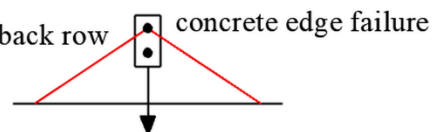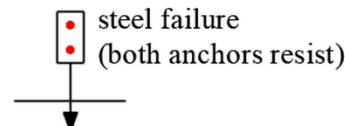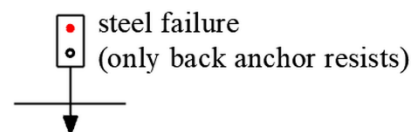
Figure 2. Considered crack initiation and concrete edge failure in case of two anchor rows according to a) EN 1992-4, b) fib Bulletin 58.

2. Scope

The aim of this study was to investigate the concrete edge failure of triangular and hexagonal anchor group configurations, which are currently not covered by the codes and guidelines such as EN 1992-4, fib Bulletin 58 or ACI 318. Furthermore, it was targeted to generate a test database because no results were found in the literature on shear loaded anchor groups of hexagonal or triangular pattern. The experiments were carried out in uncracked concrete on anchorages placed close to the concrete edge with hole clearance and were loaded perpendicular towards the concrete edge. Additionally, numerical simulations using 3D finite element analysis were carried out to obtain more information about the behavior of shear loaded anchorages.

Post-installed bonded anchors from the company fischer (FIS EM Plus) were used in the tests to enable the investigation of hole clearance on the anchorage performance and crack pattern. The numerical simulations were performed on the same anchor configurations, however, without considering the hole clearance. The results of the shear loading tests were analyzed and compared with numerical results and with calculations based on the current regulations to emphasize the differences between the test results and the codes. The corresponding test program is summarized in table 1.

3. Experimental investigations

3.1. Test program

In this study, quasi-static shear loading tests were performed on anchor groups of triangular and hexagonal configurations according to figure 3 and table 1. In all cases, the shear load was applied perpendicular and towards the concrete edge. The anchor pattern of the base plates enabled for both triangular and hexagonal groups to investigate two different test configurations by rotating the base plate by 180° for the triangular pattern and by 90° for the hexagonal pattern. However, the edge distance c_1 of the back anchor row was kept constant for all cases (see figure 3). The test parameters, such as concrete strength, anchor diameter, steel grade, anchor embedment depth, anchor spacing and edge distance were chosen in a way that failure modes other than concrete edge failure (steel failure, pryout failure) were not decisive. The test parameters are given in table 1 and in section 3.2-3.3.

Note that the verification of steel failure according to EN1992-4 and fib Bulletin 58 is beyond the scope of this current paper. However, the estimated steel failure load of a single anchor of the corresponding parameters using the largest tested edge distance ($c_1 = 240$ mm) is 147 kN, which is higher than the estimated resistance of any of the tested groups.
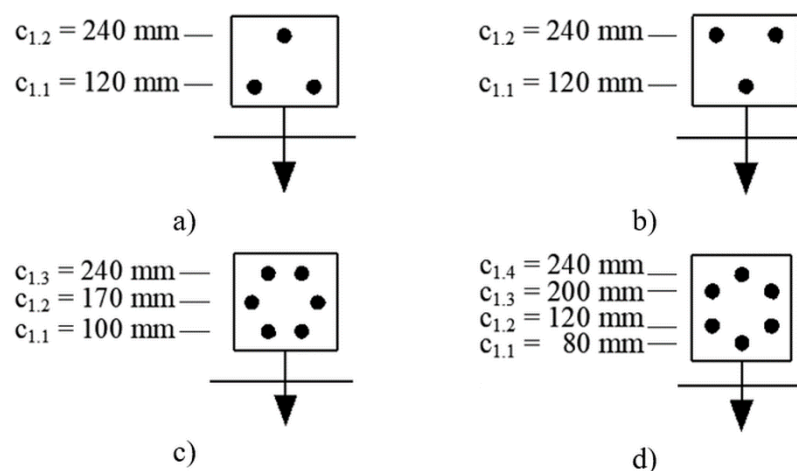

Figure 3. Investigated configurations a) Test series I., b) Test series II., c) Test series III.; d) Test series IV.

Table 1. Test program.

Test series ID	Mean concrete cube compressive strength	Embedment depth	Edge distance of the corresponding n^{th} anchor row, $c_{1,n}$				Anchor spacing in loading direction	Anchor spacing perpendicular to the loading direction	No. of tests
-	$f_{cc.m}$	h_{ef}	$c_{1.1}$	$c_{1.2}$	$c_{1.3}$	$c_{1.4}$	s_1	s_2	-
-	N/mm²	mm	mm	mm	mm	mm	mm	mm	-
I.	25.2	120	120	240	-	-	120	139	3
II.	25.2	120	120	240	-	-	120	139	3
III.	25.2	120	101	171	240	-	69.25/69.25	80/160/80	3
IV.	25.2	120	80	120	200	240	40/80/40	0/138.5/138.5/0	3

3.2. Test specimens

The shear loading tests were carried out in normal strength concrete specimens of size 163.5 cm * 163.5 cm * 50.0 cm. The specimens were provided with edge reinforcement in order to avoid the flexural failure of the specimen while applying the shear load perpendicular to the concrete edge. The dimensions of the concrete specimens and the position of the reinforcement were designed in a way that during the testing, the formation of the full-size concrete edge breakout bodies was ensured without an influence of neighboring anchor groups or the edge reinforcement. The clear distance between the closest anchors of the adjacent groups was always greater than 4 times the edge distance (c_1) of the corresponding back anchor row. The compressive strength was measured on standard concrete cubes (a = 150 mm) according to DIN EN 12390-15 [7]. The concrete mix of the corresponding concrete batches was designed according to DIN EN 206 [8], with a maximum grain size of 16 mm.

3.3. Tested anchors

The tests were carried out with an epoxy-based adhesive anchor system using M20 (d = 20 mm) steel threaded rods of grade 12.9 ($f_{u,nom}$ = 1200 N/mm²). The mean bond strength of the used adhesive was approximately τ = 30 N/mm². The effective embedment depth of the anchors was h_{ef} = 120 mm in all the tests. This corresponds to a h_{ef}/d ratio of 6.0. The anchors were installed according to the corresponding Manufacturer´s Installation Instructions (MII). The holes were drilled perpendicular to the concrete surface using steel templates with pilot-holes to ensure accurate positioning of the anchors within the group and providing an accurate edge distance. After the drilling and cleaning process, the anchors were set, and the base plate was positioned on the anchors, respectively. No installation torque was applied on the anchors, and the nut was only hand-tightened after the prescribed curing time of the epoxy mortar. The clearance holes were not filled, so the anchorages have to be considered as anchor groups with hole clearance loaded in shear perpendicular to concrete edge. The diameter of the clearance hole in the base plate was 22 mm according to table 1 of EN 1992-4.

3.4. Test setup

The shear loading tests on triangular and hexagonal anchor groups were performed using a test setup, which consisted of the following major components: (i) steel supports with an adequate distance ($4c_1$ of back row) to allow the formation of an unrestricted concrete breakout body (ii) slab tie-down to avoid the uplifting of the specimen (iii) a hydraulic cylinder and high strength threaded rod for load application, (iv) a hinge to allow the free rotation of the base plate, (v) a calibrated load cell, (vi) displacement transducers, (vii) 2 mm thick Teflon layer to minimize friction between base plate and concrete surface and (viii) a data acquisition system with computer interface. The typical test setup used for the tests is shown in figure 4. The shear load was applied to the anchors through the base plate by using the hydraulic cylinder of load capacity = 400 kN. To transfer the load from the hydraulic cylinder

into the base plate, a high strength threaded rod was used with a built-in special hinge to allow the free rotation of the base plate. The shear load applied to the anchor group was measured using a calibrated load cell (20 - 200 kN). The horizontal displacement was measured using two displacement transducers (LVDT with a measuring range of 0.01 – 75.00 mm) on the base plate (see figure 4b)).
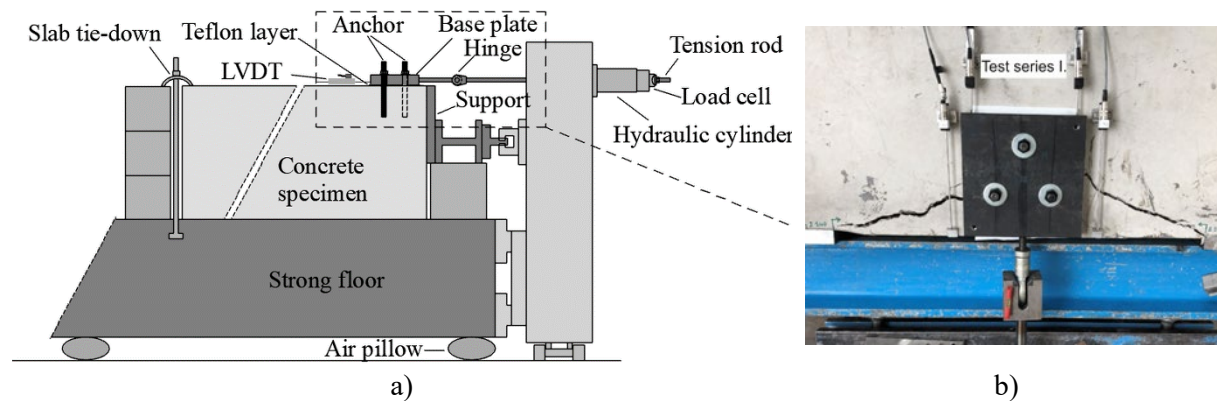

a)   b)

Figure 4. Test setup a) Drawing of the side view, b) Top view during testing.

4. Numerical investigations

The aim of the numerical investigations was to support the results obtained from the experimental program and to investigate the corresponding groups without clearance hole.

The numerical analyses were performed using the finite element Code MASA (IWB and Ožbolt, 2008), developed at the University of Stuttgart. The software is capable of performing 3D nonlinear finite element analysis of structural elements made of quasi-brittle materials such as concrete, based on a microplane material model with relaxed kinematic constraint (Ožbolt et al., 2001 [9]). For creating the 3D finite element model and for the evaluation of the numerical results, the commercial pre- and post-processing software FEMAP (Siemens) was used.

The numerical simulations were carried out in displacement control by incrementally applying the displacement in several steps. The geometry and material properties of the numerical model corresponded to the parameters of the experiments. The numerical models consisted of the following components: concrete specimen modeled using solid 4-node tetrahedral elements, steel base plate and anchors (steel rods) modeled using solid 8-node hexahedral elements, contact layer between anchor and concrete, contact layer between base plate and concrete and two types of bar elements. Contact bar elements, which can take up only compressive stresses, were used in the interface between the concrete surface and base plate to simulate a Teflon sheet, which was used in the experiments to minimize friction between steel and concrete. Bond type bar elements were applied in the contact layer between concrete and steel rod to model the bond provided by the epoxy mortar realistically. The behavior of the base plate and the anchors were assumed to be linear elastic.

5. Results and discussion

In this section, experimental and numerical results are discussed and compared to calculations based on the current recommendations given in EN1992-4 and fib Bulletin 58. The experiments were performed with hole clearance between the loading plate and the anchor rod, while the numerical investigations were performed without any hole clearance. The experimental, numerical and calculated results are tabulated in table 2. The crack pattern obtained from the experiments (one representative pattern) as well as from the numerical investigations are given in figure 5. Note that the crack pattern obtained from the numerical investigation corresponds to the failure crack pattern in the post-peak phase and the cracks, which were developed during the load distribution from row-to-row are not visible.

Table 2. Results.

Test series ID	Mean ultimate shear load Experiment[1]	Ultimate shear load Numeric[2]	$V_{u,m,Exp}$ / $V_{u,Num}$	Assumed crack initiation based on EN 1992-4	Calculated mean concrete edge resistance based on EN 1992-4[3]	$V_{u,m,Exp}$ / $V_{Rm,c,EN}$	Assumed crack initiation based on fib Bulletin 58	Calculated mean concrete edge resistance based on fib Bulletin 58[4]	$V_{u,m,Exp}$ / $V_{Rm,c,fib}$
-	$V_{u,m,Exp}$	$V_{u,Num}$	-	-	$V_{Rm,c,EN}$	-	-	$V_{Rm,c,fib}$	-
-	kN	kN	-	-	kN	-	-	kN	-
I.	80.1	105.7	0.76		47.4	1.68		88.1	0.91
II.	111.3	120.0	0.93		35.5	3.13		102.8	1.08
III.	106.2	113.7	0.93		36.0	2.95		97.9	1.09
IV.	92.4	- [5]	-		21.3	4.34		88.1	1.05

[1]Crack initiation depends on actual hole clearance and load distribution, [2] Crack initiation depends on load distribution without hole clearance, [3] Crack initiation assumed from front anchor row, [4] Crack initiation assumed from back anchor row, [5] No numerical analysis was carried out for series IV.
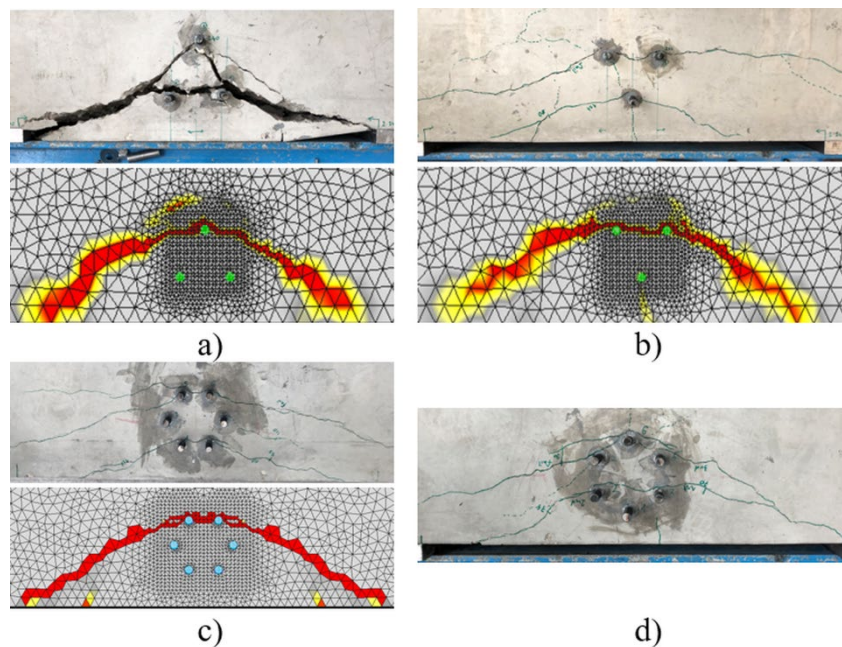

Figure 5. Crack pattern obtained from experimental and numerical investigations of Test series a) I., b) II., c) III., d) IV.

5.1. Test series I.

Test series I. was performed on anchor groups of triangular configuration with two anchors in the front row ($c_{1.1}$ = 120 mm) and one anchor in the back row ($c_{1.2}$ = 240 mm) (see figure 3a)). The mean failure load obtained from the experiments was 80.1 kN. The numerical failure load of the group was 105.7 kN, which is 24% higher than the experimental value. The difference can be attributed to the fact that the experiments were carried out with hole clearance and the numerical investigation without hole clearance. Due to hole clearance, all the anchors do not carry the applied load simultaneously and with the same stiffness, thereby leading to overloading of certain anchors. Figure 5a) shows the failure mode and crack pattern of one representative test. It can be seen that the cracking at front anchor was pronounced, which had an influence on the load distribution to the back row. This is in agreement with the findings of Grosser and Cook (2009)[10] that for anchorages with a small edge distance and a ratio spacing to edge distance smaller or equal to one, the failure load of the group may be negatively influenced by the cracks generated at the front anchor row. However, Grosser and Cook investigated rectangular anchor groups. As expected, the calculated load based on EN1992-4 (47.4 kN) is very conservative because it neglects the possible load redistribution to the back row with assuming the failure crack originating from front anchors. The failure load based on fib Bulletin 58 is slightly higher (9%) compared to the experimental value. This can be explained again by the influence of hole clearance. However, 9% deviation between the experimental and calculated results is within the general scatter considered in the CCD method for concrete edge failure (15%).

5.2. Test series II.

Test series II. was performed on anchor groups of triangular configuration with one anchor in the front row ($c_{1.1}$ = 120 mm) and two anchors in the back row ($c_{1.2}$ = 240 mm) (see figure 3b)). The mean failure load obtained from the experiments was 111.3 kN. The numerical result was 120 kN, which is just 7% higher than the experimental result. This can be explained by the fact that only one anchor was placed in the front row and the cracks initiating from front anchor had a lesser influence on the back row, so the shear force could be distributed to the back row. However, 7% deviation is within the scatter generally associated with the test results for concrete edge failure (15%). The failure load calculated based on the EN1992-4 was one-third of the mean measured ultimate load, which is very conservative. Assuming the failure crack initiation from the back anchor row based on fib Bulletin 58 resulted in 108.8 kN, which is 8% less than the measured value and represents the failure load reasonably well.

5.3. Test series III.

Test series III. was performed on anchor groups of hexagonal configuration with two anchors in the front row ($c_{1.1}$ = 101 mm). The configuration is depicted in figure 3c). The mean failure load obtained from the experiments was 106.2 kN, whereas the failure load obtained from the numerical investigation was 113.7 kN. This corresponds to only 7% difference. The crack pattern of one representative test in figure 5c shows that even if cracks at the front row have developed, the shear forces could be redistributed to the back anchor rows. The failure load calculated based on the EN1992-4 was less than one-third the mean measured ultimate load, which was also expected because only the two anchors of the front row were considered to resist the shear loads. The calculation based on fib Bulletin 58 estimated as 97.9 kN assuming the failure crack origination from back anchor row, which is 9% smaller than the measured value.

5.4. Test series IV.

Test series IV. was carried out on anchor groups of hexagonal configuration with one anchor at the front row ($c_{1.1}$ = 80 mm). The configuration is shown in figure 3d. For this case, only experiments were carried out. The mean failure load was 92.4 kN. This corresponds well to the failure load calculated based on fib Bulletin 58 (88.1 kN) assuming the failure crack origination from the back anchor. The calculated failure load based on EN1992-4 was 21.3 kN, which is very conservative. The measured mean ultimate load was more than four times this calculated value. The crack pattern of one representative test is shown

in figure 5d. It can be seen that before the failure crack originating from the back row has developed, cracks at the second anchor row were already present. However, the first cracking did not influence the failure load of the group because the force redistribution could take place before the crack width at the middle row would have become large.

6. Summary and conclusions

In this paper, experimental and numerical investigations were performed on post-installed anchor groups of triangular and hexagonal configurations. It was observed that for the configurations tested, the failure crack always initiates from the back anchor row, even in case of anchor groups, where the first cracking is associated to the front or middle anchor row. The first cracking may have an influence on the displacement behavior of the group (beyond the scope of this current paper), which might limit the design in SLS. However, this is dependent on the displacement behavior of individual anchors within the group, edge distance, spacing and hole clearance. Furthermore, calculations based on the code EN1992-4 and guideline fib Bulletin 58 were carried out to investigate, whether it would be reasonable to calculate the resistance of arbitrary anchor configurations similarly to rectangular anchor groups. The results showed that the EN1992-4 is over-conservative for the four investigated cases. The conservatism (70%-430%) is depending on the anchor pattern and hole clearance pattern. The more anchor rows result in more conservative results since the EN1992-4 considers the failure crack originating from the front row and neglects any possible force redistribution. The calculations based on the recommendations given in fib Bulletin 58 are in reasonably good agreement with the test results (between -9% and +9%).

It can be concluded that for the investigated cases, calculating the failure load by assuming the failure crack initiating from the back anchor row is reasonable. However, the tests were carried out with a given geometry and test parameters. In practice, the parameters and parameter combinations differ from case to case, which has a significant influence on the load distribution. Therefore, further tests and numerical parametric studies need to be performed on anchor groups of arbitrary configurations with a special emphasis on the displacement behavior of the anchors within the group with and without hole clearance to understand the load distribution within shear loaded anchorages better. Due to the complex failure mechanism of shear loaded anchor groups, there is a need to develop an approach that accounts for a realistic load redistribution among the anchors of a group and is capable of calculating the failure loads of anchor groups of different geometric configurations.

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