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STUDIES ON STEEL-TO-CONCRETE JOINTS WITH CONCENTRATED LOADING CONDITIONS

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Abstract. *In mixed buildings of steel and concrete an economical design depends on intelligent solutions for steel-to-concrete joints. The design and verification of steel-to-concrete joints is challenging, as the structural behaviour and the properties of different materials have to be considered. Large forces often have to be transferred in localized areas, e.g. bridge bearings, and various failure modes of steel and concrete may occur in the joints due to load concentrations. An imposed load preventing uplift and a well-placed reinforcement can strengthen these joints decisively. In this contribution, experimental and numerical investigations and recent approaches for the design of steel-to-concrete joints are presented in order to extend and harmonise current rules leading to new chances of optimisation.*

1 INTRODUCTION

Mixed buildings of steel and concrete allow to utilize the best performance of the structural materials and therefore an economical design. However the design of the joints between the different materials is often a point of discussion. Different failure modes may occur in these joints and have to be considered within the design for steel and concrete components. In case of column base plates in strip foundations, bridge bearings or on top of columns forces have to be transferred in a localized concentrated area and concrete failure mechanisms such a concrete edge failure may become decisive. Conservative assumptions for the edge influence or the contribution of supplementary reinforcement in current rules only allow for small load carrying capacities or require high edge distances. Recent research has shown that a holistic approach for the design of these joints is possible, if the failure mechanisms of the anchorage according to the fastening technology are integrated in the design concept of the component method for steel and composite structures. An economic and in comparison to concrete structures competitive design of steel and composite structures is possible, as the load-carrying behaviour in the concrete part can be captured. In the frame of this paper current research results [1], [2] are presented, where tests were conducted to develop an analytical model for steel-to-concrete- joints under concentrated loading conditions. An increase of the load carrying capacity can be reached, if the concrete components are strengthened, by considering load distributions due to edge influences and the contribution of reinforcement. A first step for standardization and implementation of the fastening technique in the design rules for these joints has partly been realized in prEN 1993-1-8 [3]. This is be presented in the contribution.

2 STATE OF THE ART

Steel-to-concrete joints may be designed according to current guidelines for steel, composite or concrete structures (see Figure 1). For steel and composite structures the design of these joints is based on the component method [4], [5] according to EN 1993-1-8 [6] and EN 1994-1-1 [7]. Within this approach the joint is subdivided into its different components, e.g. the T -stub model for the anchor plate (Figure 1 a)) or

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the web panel and flange in tension/shear for the steel column (Figure 1 b)), and the load bearing capacity of the joints is defined by the component with the smallest load bearing capacity. The component method may only be used for steel-to-concrete joints, if a failure of the concrete components can be excluded and the steel components become decisive. This is not the case for most base plates with anchors of low embedment depth or small edge distances. In addition, the influence of a grout layer between anchor plate and concrete is not addressed in the design rules [6], [7].

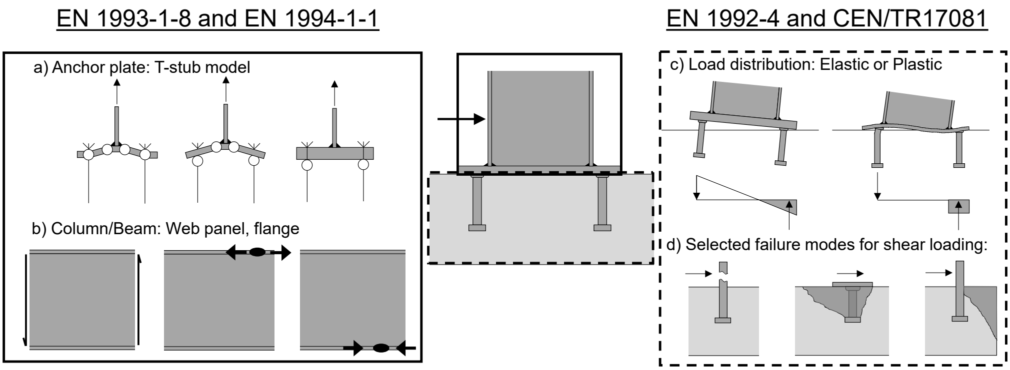

Figure 1: Steel and concrete components for column base plates acc. to current design rules

The concrete components may be designed according to EN 1992-4 [8] based on the CC-method [9]. In these guidelines different failure modes for anchors in concrete under tension and shear are defined (see Figure 1 d)). Different parameters such as edge influence, influence of a grout layer, cracked and non-cracked concrete and different kinds of fasteners are considered. The use of supplementary reinforcement is covered in a conservative way as the interaction of steel and concrete components regarding the load transfer is not considered. In addition, assumptions have to be made regarding the load distribution among the headed studs. Axial forces in the anchors may be distributed between the anchor rows according to an elastic design concept assuming that all anchors have the same stiffness and that the anchor plate is sufficiently rigid or in case of flexible anchor plates according to a plastic design concept [10], see Figure 1 c).

For anchor plates under shear close to the edge assumptions for the load distribution between the anchor rows and for the crack propagation have to be made. In current rules [8] it is assumed that the crack failure starts from the anchors closest to the edge and that the embedment length of the supplementary reinforcement is defined by the assumed concrete breakout body. In this case, it is assumed that a load redistribution to the anchors remote to the edge is not possible and the bearing capacity of the joint is determined in a conservative way by the rules.

3 INVESTIGATIONS ON STEEL-TO-CONCRETE JOINTS WITH CONCENTRATED LOADING CONDITIONS

3.1 Experimental investigations

Fifty tests were conducted on anchor plates under shear loading with 2- and 4-sided edge influence (Figure 2) at the MPA (Materials Testing Institute) of University of Stuttgart to gather information about the load bearing behaviour of steel-to-concrete joints under concentrated loading conditions and to apply these results as a validation for further numerical investigations. In a second step a design model for steel-to-concrete joints was developed based on the experimental and numerical studies.

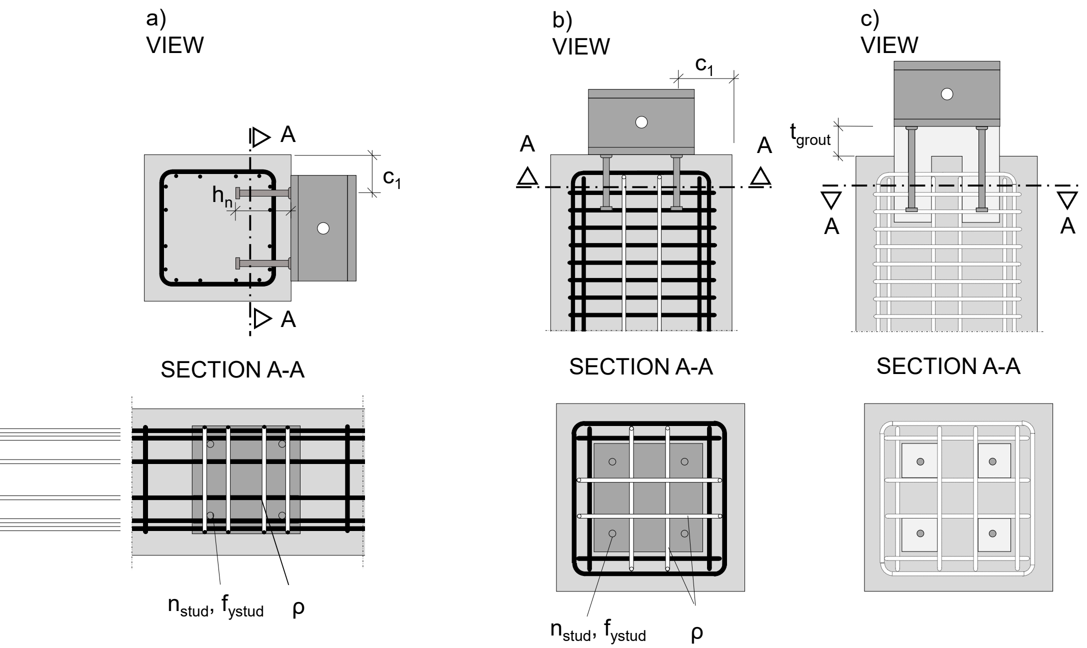

Figure 2: Test specimen for test on anchor plates with 2- sided edge influence (a) and with 4-sided edge influence without (b) and with grout layer (c)

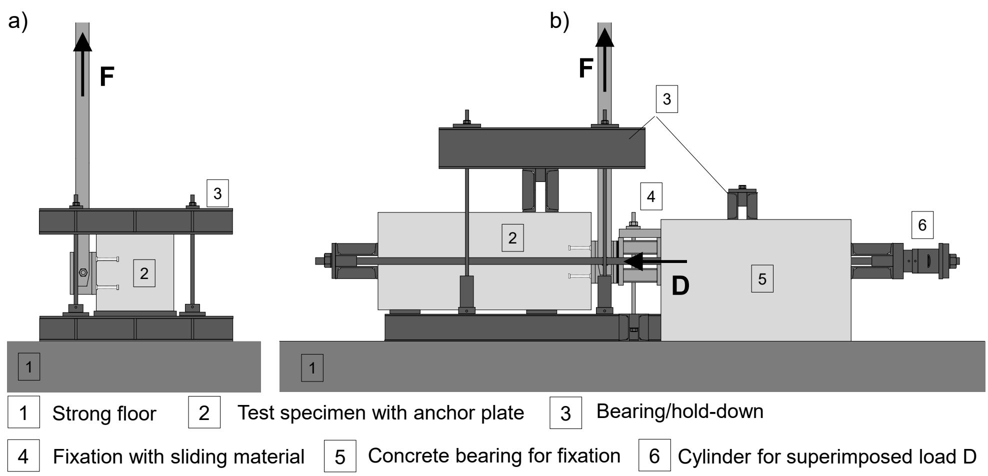

Figure 3: Test setup for tests on anchor plates with 2- sided (a) and 4-sided (b) edge influence under shear loading

Table 1: Testing scheme of shear tests on anchor plates with 2- and 4-sided edge influence

Series	Constraint/ superimposed load D[1)]	c_1 [mm]/ Edge influence [sides]	ρ [mm]	h_n [mm]	n_{stud}	t_{grout} [mm]	C_c	$f_{y,stud}$	n_{tests}
B1	B1-1/B1-2: no B1-3: fixed	100/ B1-1: 2 B1-2/B1-3: 4	1 ø12	150	4	-	C20/25	S235J2+C450	3
R2	R2-1/R2-2: no R2-3: fixed	100/ R2-1: 2 R2-2/R2-3: 4	2 ø12	150	4	-	C20/25	K800	3
R3	no	100/ R3-1(1)/R3-1(2): 2 R3-1(1)/R3-2(2):4	2 ø12	150	4	-	C20/25	K800	4
R4	R4-1/ R4-2: no R4-1-3/R4-2-3: fixed	100/ R4-1: 2 R4-2/R4-1-3/ R4-2-3:4	2 ø12	100	4	-	C20/25	R4-1/ R4-2/R4-1-3: K800 R4-2-3: S235J2+ C450	4
R5	R5-1/R5-2: no R5-3: fixed	100/ R5-1:2 R5-2/R5-3: 4	2 ø12	200	9	-	C20/25	K800	3
R6	R6-1-1/R6-1-2/R6-2-1/R6-2-2: no; R6-1-3/R6-2-3/R6-3-3/ R6-4-3: fixed	75-200/ R6-1-1/R6-2-1: 2	2 ø12	150-200	4	-	C20/25 - C50/60	K800	8
Z1	Z1-1: fixed; Z1-2: D[1)] = 50% Z1-3: D[1)] = 100% Z1-4: D[1)] = 150%	100/ 4	1 ø12	150	4	-	C20/25	S235J2+C450	4
Z2	Z2-1: fixed; Z2-2: D[1)] = 50% Z2-3: D[1)] = 100% Z2-4: D[1)] = 150%	100/ 4	2 ø12	150	4	-	C20/25	S235J2+C450	4
Z3	Z3-1: fixed; Z3-2: D[1)] = 50% Z3-3: D[1)] = 100% Z3-4: D[1)] = 150%	150/ 4	2 ø12	150	4	-	C20/25	S235J2+C450	4
Z4	Z4-1: fixed; Z4-2: D[1)] = 50% Z4-3: D[1)] = 100% Z4-4: D[1)] = 150%	250/ 4	2 ø12	150	4	-	C20/25	S235J2+C450	4
Z5	Z5-1: fixed; Z5-2: D[1)] = 100% Z5-3: D[1)] = 150%	150/ 4	2 ø12	150	4	20	C20/25	S235J2+C450	3
Z6	Z6-1: fixed; Z6-2: D[1)] = 100% Z6-3: D[1)] = 150%	150/ 4	2 ø12	150	4	20	C20/25	S235J2+C450	3
Z7	Z7-1: fixed; Z7-2: D[1)] = 100% Z7-3: D[1)] = 150%	150/ 4	2 ø12	150	4	50	C20/25	S235J2+C450	3

[1)] [%] load bearing capacity of the respective reference test of each series

Aim of the tests was to initiate different failure modes and to investigate the load distribution between the anchor rows considering the edge influence. Therefore, the following parameters (see also Figure 2) were varied within the specified limits according to Table 1: Edge distance c_l (75, 100, 150,200 and 250 mm), reinforcement ratio ρ between the two outer anchor rows parallel/ perpendicular to the load direction ρ (1x ø12 mm and 2x ø12 mm), grout layer between anchor plate and concrete t_{grout} (20 and 50 mm), embedment length of headed studs h_n (100, 150 and 200 mm), number of headed studs n_{stud} (2x2 and 3x3), material of the headed studs $f_{y,stud}$ (S235J2 + C450 and K800), concrete strength C_c (C20/25 and C50/60).

In all tests rigid anchor plates with a thickness of 30 mm were loaded by a shear force with an eccentricity of 100 mm. Therefore, the anchor plate was loaded in tension and shear. In several tests the anchor plate was additionally constraint by a steel block and fixed perpendicular to the loading direction (see Table 1 "fixed") or additionally loaded by a superimposed load D that prevents the uplift of the anchor plate (see Figure 3). As a result, the headed studs were loaded by shear only. A sliding material was used to ensure a frictionless contact between steel block and anchor plate. This setup is adapted to investigate the load bearing behaviour of an anchor plate, e.g. in a bridge bearing or a loaded column. In order to identify the influence of the different parameters, the testing scheme in Table 1 was chosen in a way that reference tests had been defined from which the other tests differed by only one single parameter. Thus, the influence of the various single parameters could clearly be identified.

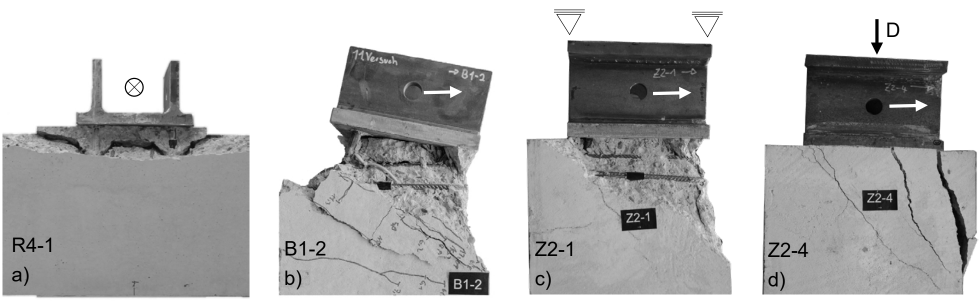

Figure 4: Different concrete failure modes of shear tests with anchor plates under edge influence:
a) Concrete cone failure, b) Concrete edge/Pry-Out failure, c) Concrete edge failure, d) Concrete edge failure with restrained crack propagation due to a superimposed loading

Different failure modes could be observed, mainly influenced by the edge distance, constraint of the anchor plate or the superimposed load and the material of the headed studs (Figure 4). The observed failure modes matched with the concrete failure modes according to the design rules of fastenings [8]. In most of the tests a concrete failure towards the loaded edge could be observed. The cracks propagated from the front as well as from the back row. The crack propagation of the tests indicated that the load can be distributed from the front to the back row in case of a concrete edge failure. The tests showed, that the edge distance had a strong influence on the load distribution and the failure mechanism of the joint. If a free rotation of the anchor plate was possible, a pry-out mechanism could be observed in the tests, due to the eccentric loading of the anchor plate, see Figure 4 a), b). In this case, the load bearing capacity decreased in tests with shorter embedment depth. If the uplift of the anchor plate was prevented by a fixation or a superimposed load, higher load bearing capacities could be achieved. In all tests with a fixed anchor plate and a S 235J2+C450 steel for the headed studs, a ductile failure mechanism developed by forming a plastic hinge in the headed studs at the base of the shank. In the tests with a fixed anchor plate and a high strength material of the headed studs, a shearing-off of all headed studs occurred. In the tests with an additional superimposed load, higher load bearing capacities could be achieved compared with tests with a fixation of the anchor plate. It could be observed, that the crack development happened at higher levels of the applied shear force. It may be assumed that the superimposed load compresses the concrete and prevents the cracking of the concrete, see Figure 4 c), d).

A higher load bearing capacity could be achieved in the tests with higher reinforcement ratio (Series R2, Z2) compared with tests with a lower ratio (Series B1, Z1). The crack propagation was restrained by the reinforcement and a ductile load bearing behaviour of the anchor plate could be observed. In the tests with a cracked concrete (Series R3), no significant influence of the concrete condition on the load bearing behaviour could be observed. It may be assumed that the crack propagation of the cracks induced before the test was restrained by the reinforcement.

An increase of the load bearing capacity was also reached in all tests with an increased concrete strength (Series R6). The load increase was in accordance with the estimations according to the current rules [8]. In the tests with 3x3 headed studs (Series R5) the assumption of a rigid anchor plate could be verified by monitoring the strains in the headed studs with strain gauges (SGS). An elastic load distribution of the axial forces could be observed.

For the tests with a grout layer (Series Z5, Z6, Z7), the grouting mortar PAGEL® V1®/50 was used. At the day of testing, the average strength of the mortar was $f_{cm,cyl}$ = 61 N/mm^2. The tests showed that by increasing the grout layer, it was more likely that the steel failure of the headed studs governed the load bearing behaviour. The load bearing capacity decreased compared with the tests without a grout layer (Series Z3). It may be assumed that the grout layer cracks and deforms at a lower load level than the enclosed concrete when increasing the load. This results in an increased loading of the headed studs by shear and bending.

3.2 Numerical investigations

The FE program MASA [11] was used for the numerical studies. The numerical model was validated based on the test results by comparing the maximum loads and the failure modes. The numerical recalculations of the tests suggested that the stirrups placed next to the headed studs are the most effective, whereas the stirrups remote from the studs are only partially loaded.

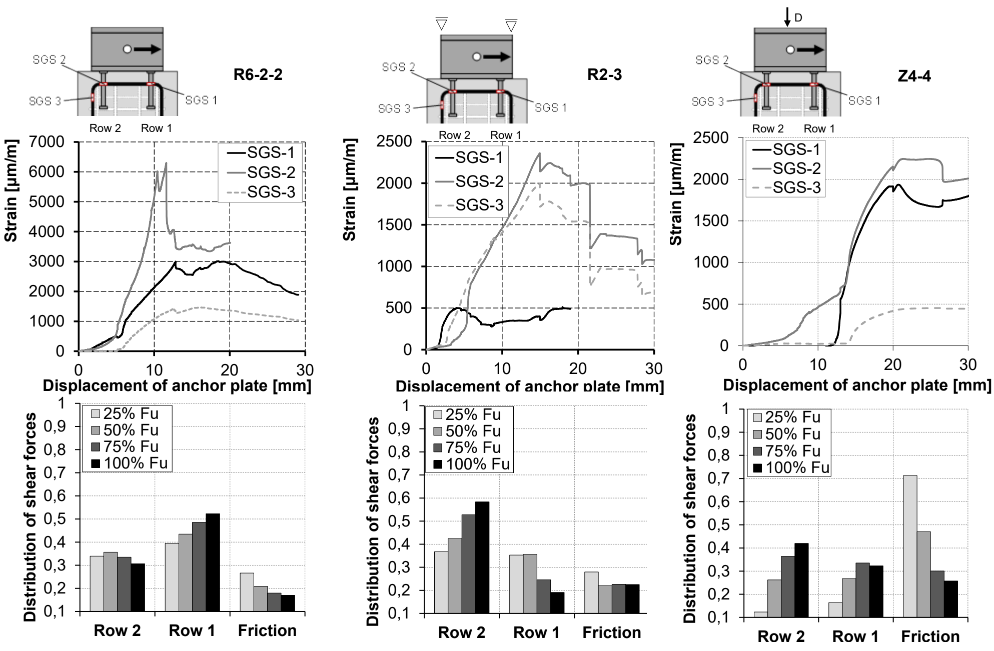

Figure 5: Evaluation of load distribution of the shear forces by monitored strains with strain gauges (SGS) in tests (top) and determined forces in the numerical investigations (bottom)

The load bearing behaviour of the joint regarding the distribution of the shear forces considering edge influences and friction forces was investigated in further numerical studies. In the tests, the load distribution was investigated by monitoring the strains of the strain gauges placed on the stirrups next to the different rows of the headed studs (Figure 5, top). In the numerical studies the shear forces transferred by friction and by the section at the base of the headed studs in the different rows were determined for different load levels and compared to the strains monitored in the tests, see Figure 5, bottom.

In the tests with a free rotation of the anchor plate and sufficient edge distance, the loads were distributed to the loaded side and mainly transferred by row 1, due to a pry-out failure mechanism (R6-2-2). In tests with short edge distances and a fixed anchor plate, the stirrups next to row 2 was highly activated (R2-3). When increasing the load level, the shear forces were distributed from row 1 to row 2, due to concrete edge failure and the shear forces were mainly transferred by row 2.

In the tests with an additional superimposed load and sufficient edge distance the shear forces were distributed equally between the anchor rows (Z4-4). The superimposed load prevented a pry-out failure as well as spalling of the concrete edge, and a steel failure of the headed studs governed the load bearing behaviour of the anchor plate. When decreasing the superimposed load or the edge distance, concrete failure mechanisms were more likely to govern the load bearing behaviour of the anchor plate. In all tests, a significant amount of shear forces was transferred by friction. Especially in the tests with a superimposed load a huge amount of shear was transferred by friction. At higher load levels the relative amount of shear transferred by friction decreased (Figure 5, bottom), however, the total amount increased, due to an increase of the resulting compressing force.

3.3 Conclusions

In the following, the main suggestions for a design model according to the presented experimental and numerical investigations are given. The failure mechanisms observed in the tests match with the failure mechanisms according to current design concept of the fastening technique [9] and current approaches [12], [13], [14], [15]. A load redistribution of the shear forces should be considered. The shear forces may be redistributed, if a concrete failure mechanism occurs. In case of a failure of the first anchor row, the shear force is distributed and transferred by the other anchor rows. Therefore, an increase of the load bearing capacity is possible and a failure of the whole joint is only obtained, when the rows on the non-loaded side have failed due to concrete or steel failure. The load distribution of the shear forces mainly depends on the edge distance and the constraints of the anchor plate (fixation/ superimposed load). An additional superimposed load increases the load bearing capacity, since an uplift of the anchor plate is prevented and the crack propagation is restrained. The determined load bearing capacity of a joint may be increased, when considering forces transferred by friction. Higher loading bearing capacities may also be achieved by considering the load bearing capacity of the stirrups placed next to the headed studs. The negative effects of a grout layer on the load bearing behaviour of anchor plate should be considered. For this propose the approaches by Fichtner [16] and Mallée [17] may be used on the safe side.

4 COMPONENT MODEL FOR STEEL-TO-CONCRETE JOINTS WITH CONCENTRATED LOADING CONDITIONS

4.1 General

Based on the tests, a design model for anchor plates under eccentric shear loading and an additional superimposed load was developed. An approach based on a strut-and-tie model as a typical approach of concrete design was not feasible, because the compression strut close to the edge governs the design and therefore, only small resistances in case of small edge distances may be calculated according to that model. Thus, the failure modes of the developed model are based on fastening technique [8].

4.2 Single components under tension und shear

The component model for steel-to-concrete joints under concentrated loading is based on existing design concepts for the failure modes of single components. The components, concrete cone, concrete edge failure, steel failure of the headed studs with and without consideration of a grout layer, pull-out and pry-out failure according to the CC-method [8], [9] are expended by approaches [12], [13], [14], [15], [16], [17] to consider a grout layer, supplementary reinforcement and additional failure modes such as concrete strut failure.

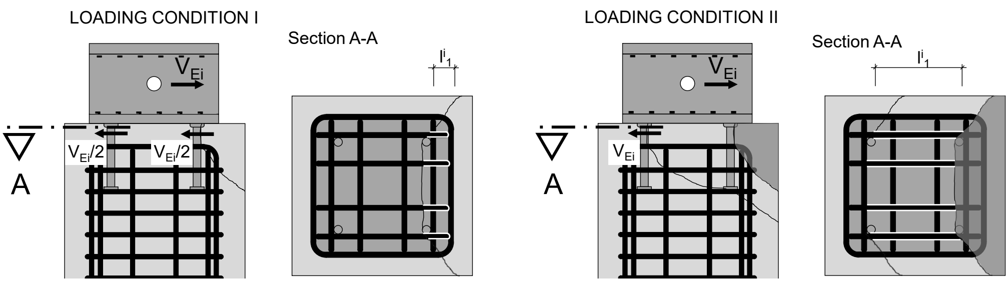

Figure 6: Distribution of shear forces and embedment lengths for loading condition I and loafing condition II in case of a concrete edge failure

The load bearing capacity of the joint can be increased, if the supplementary reinforcement placed next to the headed studs prevents a spalling of the concrete edge and the failure of the reinforcement governs the load bearing behaviour. For this propose a sufficient embedment length of the stirrups in the assumed breakout failure body of the concrete is a necessary condition, otherwise a concrete failure occurs due to an anchorage failure of the reinforcement. However, even with a sufficient embedment length of the stirrups the increase of the load bearing capacity due to supplementary reinforcement is limited by a concrete cone failure in between the stirrups and a failure of the concrete strut. This may be prevented by a sufficient embedment length of the headed studs. If the failure of the stirrups can be excluded, a common load transfer of concrete and reinforcement is considered according to [12] for the verification of the anchor rows in tension. For the verification of the rows in shear, the common load transfer is neglected on the safe side, because of an early crack propagation of the concrete, due to small edge distances.

The influence of an additional grout layer is considered by a reduction of the shear strength of the headed studs. In case of a small grout layer ($0{,}5\ d_{stud} < t_{grout} < 5d_{stud}$) the shear strength is reduced as a function of the grout thickness according to Fichtner [16]. For thicker grout layers ($t_{grout} > 5d_{stud}$) the studs in row 1 are assumed to be loaded in bending and the shear strength of row 1 depends on the moment resistance of the headed studs according to Mallée [17].

The load distribution between the different rows is considered by different loading conditions. Depending on the loading condition, forces are redistributed between the different rows and different concrete breakouts and appropriate embedment lengths can be derived, see Figure 6. In loading condition I, it is assumed that cracks propagate from the front row to the loaded edge (Figure 6, left). The shear forces are distributed equally between the different rows. In loading condition II this crack pattern is finalised by a developed breakout failure from the front row to the loaded edge (Figure 6, left). Therefore, the forces are redistributed to the back row assuming cracks, which propagate from the back row to the loaded edge. In case of a steel failure of the headed studs or a pry-out failure in loading condition I, loading condition II does not apply and a redistribution of the shear forces is not possible. If an anchor row is compressed by a superimposed load, it is assumed that a verification for pry-out failure is not necessary.

4.3 Component model

In the following, an analytical design model is proposed for steel-to-concrete joints under concentrated shear loading, which considers the load distribution and the resistances depending on the different failure mechanisms and loading conditions. For the definition of the shear components the loading of the joint is split into a bending moment for the definition of the axial forces and into pure shear forces, see Figure 7.

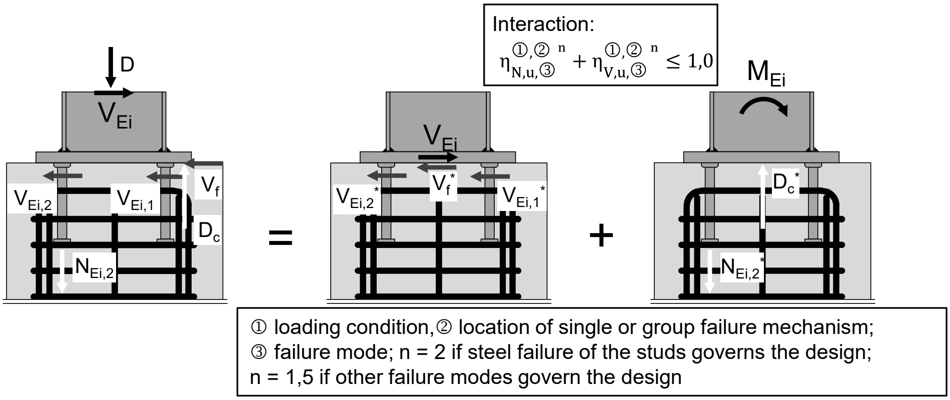

Figure 7: Definition of the acting loads and interaction equation for steel-to-concrete joint with eccentric shear loading

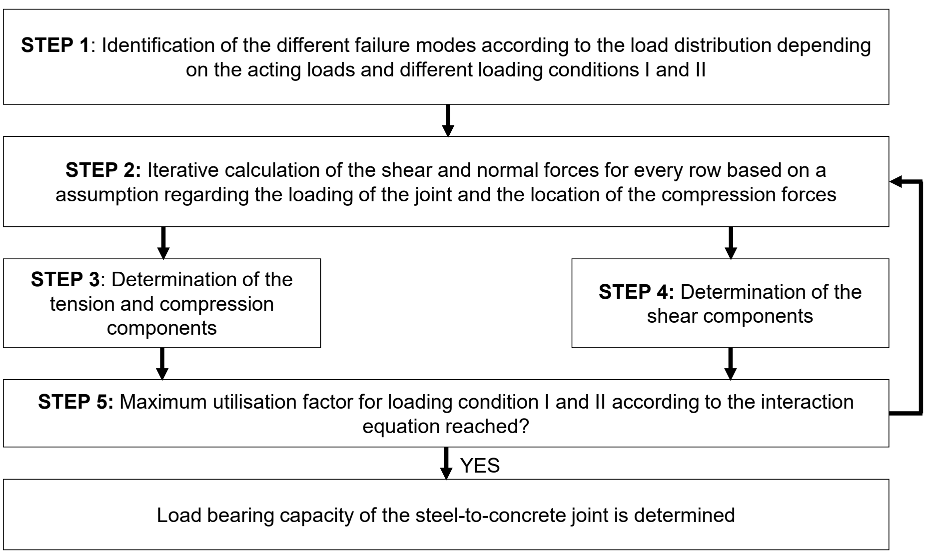

Figure 8: Flow chart for the design approach for steel-to-concrete joints [18]

This definition applies to all failure modes given in section 4.2. The shear forces transferred by friction are considered by the equilibrium of the axial forces and a friction coefficient. The axial forces are distributed between the different rows according to an elastic design concept. In case, the joint is loaded by an additional superimposed load, the superimposed load is distributed proportionally to the tensions forces in each row. The resulting axial, shear and friction forces under consideration of the superimposed load (Index "*", see Figure 7) are used for the verification. The verification for every component has to be done iteratively considering the different loading conditions and every row individually. The load bearing capacity of the joints is determined by the maximum utilisation factor according to the interaction equation given in Figure 7. For the different interactions, it has to be distinguished between different failure modes, their location (row1, 2 or 3) and single failure or group failure mechanism. Therefore, the interaction for single failure mechanisms only apply, if failure mechanisms become decisive at the same location and in the same loading condition. A simplified flow chart for the determination of the load bearing capacity of steel-to-concrete joints is given in Figure 8.

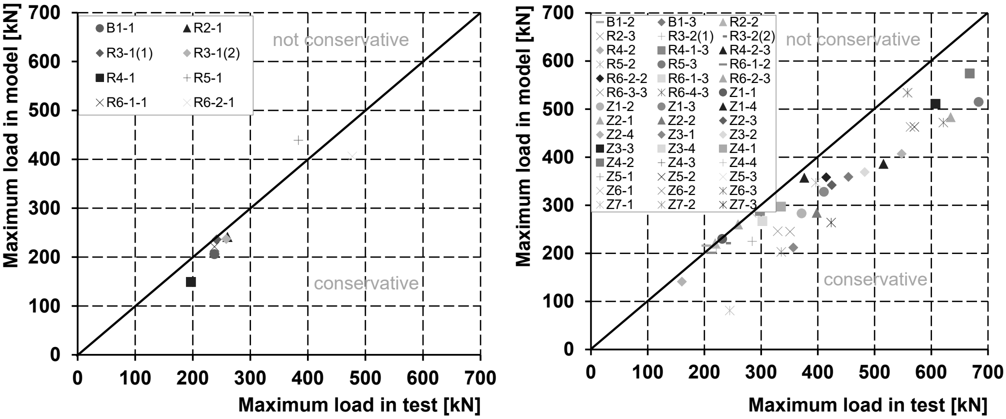

Figure 9: Comparison of maximum loads of the analytical model and the experimental results for joints with 2-sided edge influence (left) and with 4-sided edge influence (right) [2], [18]

The results from the analytical design model for steel-to-concrete joints with 2- and 4-sided edge influence for the different failure modes and load bearing capacities agree sufficiently well with the test results, see Figure 9. A derivation of design values for the component model for steel-to-concrete joints under concentrated loading is given in [18].

4.4 Implementation in current design concepts and remaining issues

The presented design model considers the contribution of the reinforcement, friction forces, a superimposed loading and the influences of a redistribution of the shear forces on the load bearing behaviour of steel-to-concrete joints in concentrated loading conditions and allows an economic and feasible design. The design model is based on the design concept of the fastening technique and its failure modes. Therefore, an easy implementation in the current design rule for fastenings in concrete [8] is possible. A first step for implementation in the design concept for joints according to the component method has partly been realized in prEN 1993-1-8 [3]. The new given opening clauses in Annex A (A. 17, A. 19) and Annex D (D. 1.1) point out, that for the design of a steel-to-concrete joints a verification of the concrete components according to the fastening technique [8] is necessary and allow a consideration of an increased resistance due to supplementary reinforcement. As a result, a holistic design concept for steel-to-concrete joints with compatible design rules considering steel as well as concrete components is possible.

However, there are some remaining issues, as described in the following. A possible reduced resistance of the anchorage, due to a grout layer is not considered in [3] and an additional verification for a steel failure of the anchorage in the grout layer - as suggested within this contribution - is not required. This may lead to an unsafe design in some cases. The presented design concept was only verified for a maximum of 3x3 anchorages. For configurations with larger anchor plates the plastic design concept according to CEN/TR17081 [10] seems a promising approach, which may be extended for joints in concentrated loading conditions. In this case, the possible flexible behaviour of the anchor plate may be considered according to the T-Stub model [3], [18]. The CC-method of the fastening technique [8] is a force-based concept, in contrast to the component method [6] considering also the stiffness and deformation of a joint. In terms of stiffness and deformation the concrete components in steel-to-concrete joints in tension without edge influences may be calculated according to [12]. An approach adjusted for joints loaded in shear was introduced in [13]. These approaches are not verified for steel-to-concreted joints in concentrated loading conditions, because of the complex load bearing behaviour due to edge influences and load redistributions.

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