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Studies on the load-carrying behaviour of steel-to-concrete joints with headed studs for normal and shear loads

Steel and composite structures usually have interfaces to concrete walls or concrete foundations. The design and verification of the interaction between steel and concrete is challenging because the load-carrying behaviour as well as the different material properties have to be taken into account. Steel-to-concrete joints can be realised economically and with comparatively little effort by using fasteners such as headed studs for the anchorage in the concrete. Recent investigations have shown that a holistic verification of joints is possible, if the concrete failure mechanisms are integrated into the concept of the component method of steel and composite structures. This allows an economical verification that is competitive with pure concrete solutions because the load-carrying behaviour in the concrete is captured with the concrete components and the steel components of the joints do not have to be oversized to avoid failure in the concrete. The load-carrying capacity of the steel-to-concrete joints can effectively be improved by taking into account the reinforcement which allows for a significant increase of the resistance of the concrete components. By arranging the reinforcement in the area of the fasteners, it is possible to achieve a higher load-carrying capacity and, with a suitable design of the reinforcement, also a ductile behaviour of the joint. In the following article, joints are described that were studied in the dissertation (Ruopp, 2020) and were investigated with regard to the above-mentioned aspects. The article concludes with an outlook on the normative implementation.

Keywords anchor plate; component method; composite structures; elastic and plastic design approach; fastening technology; headed studs; steel-to-concrete joints

1 Introduction

The range of applications for steel-to-concrete joints in steel and composite constructions is diverse, as different construction requirements are imposed, for example, on given geometric boundary conditions such as the horizontally lying studs close to the edge or on the loads to be transferred such as the beam-to-wall joint (Fig. 1). Especially for the transfer of large forces, which ranges from simple applications such as a hinged shear joint to column bases with combined loading by normal and shear forces and moments, the design of steel-to-concrete joint represents a challenge for the designing engineer. In addition, the type of verification following the fastening technique and design of concrete according to EN 1992-4 [1] or the design of steel concrete composite structures according to EN 1993-1-8 [2] and EN 1994-2 [3] is not in conformity and a starting point of difficult discussions in practice. As a result, these joints are often oversized, so that failure in the area of the concrete is excluded, e. g., with the help of long anchor bolts or embedded profiles as a load-distributing structure in the concrete.

Reinforcement can efficiently be used to transfer high forces in the joint, also when fasteners such as headed studs are used, as the forces can be suspended back into the interior of the structure. Recent investigations [4,5] on typical behaviour of components in concrete have shown that the combined action of reinforcement and concrete may lead to a decisive increase of the carrying capacity of these joints. The objective of Ruopp [6] was to verify the application of these new approaches for concrete components at joints in steel and composite structures with large loadings. In addition, also joints were investigated where, due to the arrangement of fasteners close to the edge, reinforcement, which may be taken into account, is present at the concrete in anyway.

2 State-of-the-art and design concepts

The design concept for large anchor plates was developed based on the component method [7], which distinguishes between different failure modes and the characterised structural behaviour of the single components. The component method according to EN 1993-1-8 [2] represents a useful analytical verification concept for steel joints, which is also extended for steel-to-concrete joints. Investigations [8] have shown that for the verification of these joints, the existing steel components can be enhanced by possible concrete failure mechanisms according to EN 1992-4 [1] on the basis of the CC-method [9]. Provided that suitable load-deformation relationships are available for the concrete components, the load-carrying behaviour of the joint including its ductility can be influenced by a suitable parameter selection. Especially in the area of column bases, investigations have shown that a ductile load-bearing behaviour of the anchor plate can be obtained by targeted design of the components [10].

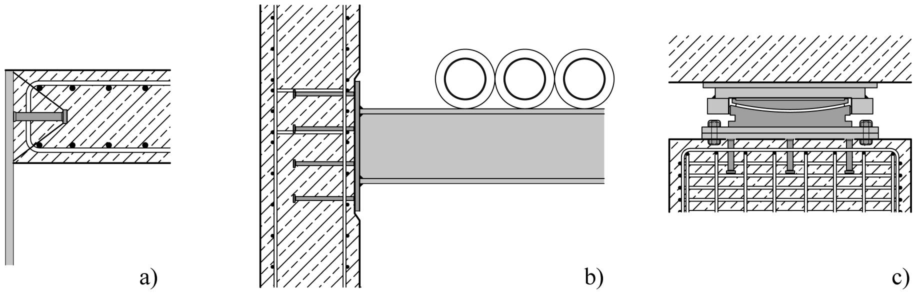


Fig. 1 Overview of the application scenarios investigated in [6]: a) composite girder with horizontally lying studs close to the edge; b) anchor plate with headed studs as beam-to-wall joint; c) anchor plate with headed studs for bearings

For the design of steel-to-concrete joints, the resulting forces from the internal forces acting on the joint must be determined at the level of the fastener and compared with the load-carrying capacity of the fastener under tension, shear load or combined tension and shear load. According to [1], the verification concept established is based on an (elastic) linear distribution of the forces in the concrete, assuming a rigid load-carrying behaviour of the anchor plate. In particular for joints with a multi-row fastener arrangement, this design concept is conservative, since the anchor row subjected to the highest load is decisive for the design and load redistributions in the joint due to the ductile load-carrying behaviour of the anchor plate are neglected [11].

Deformation-based analytical models were developed in [5], with which the combined load-carrying effect of concrete and reinforcement can be determined, leading to a remarkable increase of the ultimate resistance compared with typical design approaches of the fastening technique. The models were developed for the individual fasteners under tension and then integrated into the concept of the component method. Based on systematic intensive investigations within the scope of [6], this design approach was extended and applied to different cases of steel-to-concrete joints (see Fig. 1).

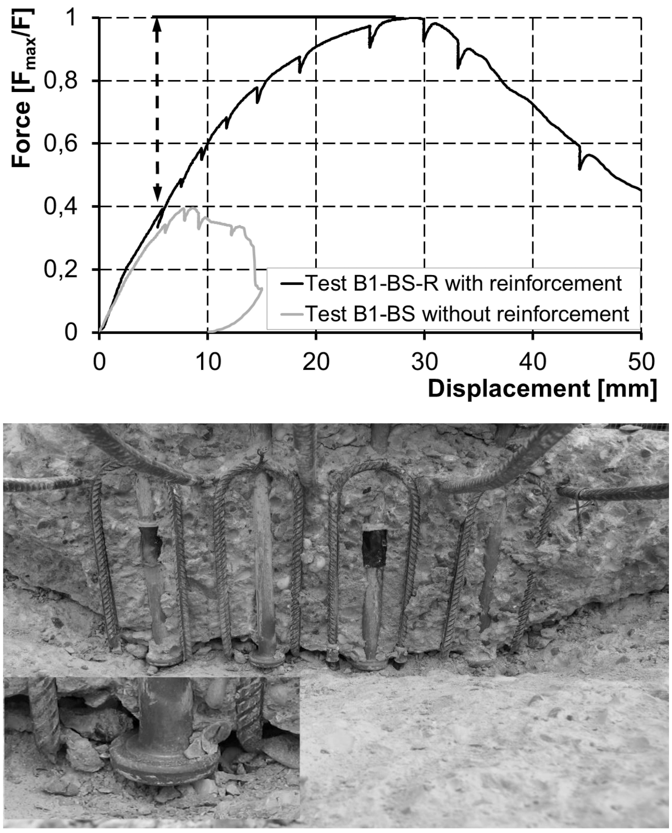


Fig. 2 Influence of supplementary reinforcement (above) [5] and ductile steel failure of supplementary reinforcement (below). On the photograph below, the deformed supplementary reinforcement due to ductile steel failure can be seen [12]

Significant increases in ultimate load can be achieved due to stirrup reinforcement, also for anchor plates with a close-edge arrangement (Fig. 2). Depending on the thickness of the anchor plate and the amount and position of stirrups, even a ductile steel failure of the headed studs can be reached, in spite of the influence of the edges. In principle also in fastening technique [1], reinforcement located at the fasteners may be taken into account; however, it has not yet been possible to consider reinforcement for both load directions and for combined loading of tension and shear. Especially for shear loading, only limited models are available for the combined load-bearing behaviour of the reinforcement and the concrete.

The attempt to strengthen the carrying capacity of anchor plates with headed studs by additional stirrups is, however, limited by a special failure mechanism, which was first discovered in [5] and which is not yet included in EN 1992-4 [1]. Especially for short fasteners with a small anchorage length, a breakout failure of the concrete between the reinforcement may occur (Fig. 3).

Furthermore, when designing steel-to-concrete joints under shear loading perpendicular to the edge, conservative assumptions are currently made in accordance with [1] with regard to shear load distribution because only the row close to the edge is considered for shear load transfer. Also for this, [6] proved a more favourable carrying behaviour as soon as sufficient reinforcement allows for a load redistribution in cracked concrete. In the following, the results of the dissertation [6] are presented specifically for the configurations shown in Fig. 1. The results of investigations on large anchor plates with shear loading, also covered in [6], can be found in [11]. Among others, the numerical and experimental results of the tests

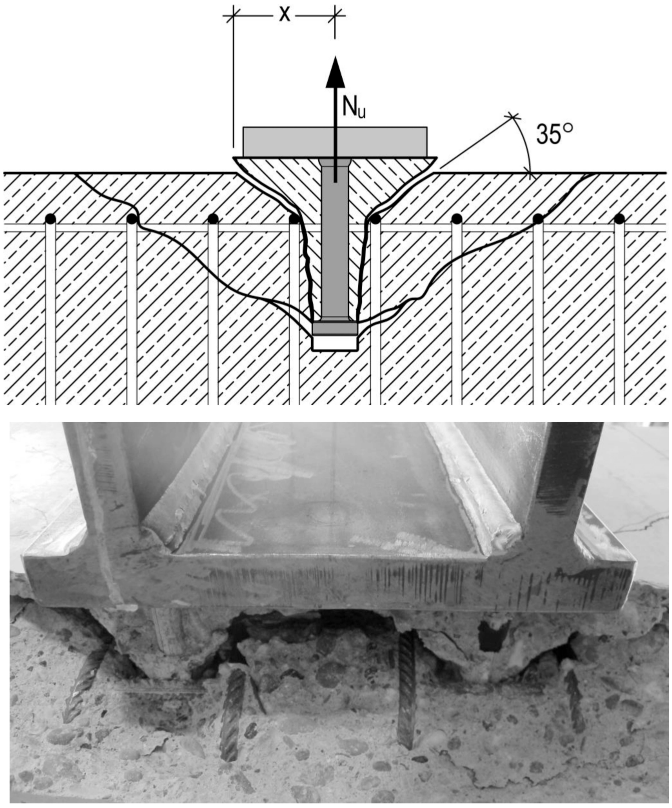


Fig. 3 Concrete breakout between the reinforcement

with large anchor plates form the basis of the analytical models in Section 4.4.

3 Experimental and numerical investigations

3.1 General

The dissertation [6] is based on three research projects [13–15] and specific investigations are summarised in the following. The focus is placed on the load-carrying behaviour and the influence of the supplementary reinforcement of the joints. For further aspects, such as influences on the load distribution of the normal and shear forces depending on characteristics of the anchor plate as well as the influence of the edges in case of a shear loading are dealt with in the related research reports as well as in the dissertation.

3.2 Investigations of horizontally lying headed studs close to the edge under tensile loading

In steel-concrete-composite girders, the transfer of shear forces between steel and concrete is typically realised by headed studs close to or far from the edge. Horizontally lying headed studs close to the edge allow thin concrete slabs to be used as concrete flanges. They are either placed in a middle position with a concrete slab to both sides of the steel girder or as part of an edge girder (Fig. 4). Due to the smaller edge distances of the headed studs to the concrete surface, however, in case of longitudinal shear, splitting failure of the concrete may occur resulting in a reduction of the load-carrying capacity. In accordance with EN 1994-2 Annex C [3], the design value $P_{\mathrm{Rd,L}}$ of the longitudinal shear resistance in the composite connection between steel and concrete is calculated with Eq. (1).

$$P_{\mathrm{Rd,L}} = \frac{1.4 \cdot k_{\mathrm{v}} \cdot (f_{\mathrm{ck}} \cdot d_{\mathrm{s}} \cdot a'_{\mathrm{r}})^{0.4} \cdot \left(a/s\right)^{0.3}}{\gamma_{\mathrm{V}}} \quad (1)$$

where:

k_{v} is the factor for position of the shear connection;
f_{ck} is the characteristic cylinder strength of the concrete [N/mm^2];
d_{s} is the diameter of the shank of the stud [mm];
a'_{r} is the effective edge distance [mm];
a is the horizontal spacing of studs [mm];
s is the spacing of stirrups [mm];
γ_{V} is the partial factor.

To prevent an early pull-out failure, a minimum anchorage length v of the headed studs is required according to [3] (see Fig. 4). This may lead to comparatively long headed studs that are uneconomical and difficult to realise in practice (see [15]). As pure construction rule, influencing parameters such as the ratio of the reinforcement or the concrete grade cannot be considered. With the increase of the thickness of the concrete flange, the longitudinal shear capacity according to Eq. (1) can be increased, but also longer headed studs are required due to the steeper compression strut inclination of the angle β according to Fig. 4.

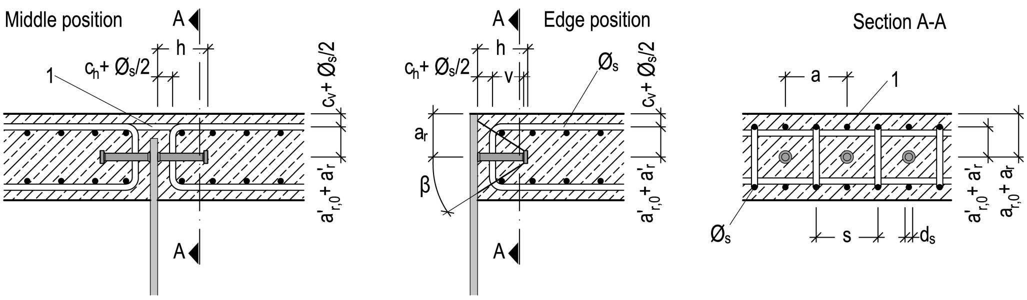


Fig. 4 Geometric boundary conditions for horizontally lying headed studs close to the edge according to [3]

Within six pilot tests, the reinforcement ratio, the embedment length of the headed studs and the edge distance of the headed studs were varied. The selected parameters are listed in Tab. 1. The test setup is given in Fig. 5. The parameters of the test specimens were chosen in the way that the boundary conditions of EN 1994-2 for tensile failure of the headed studs as given in Fig. 4 were not fulfilled. The objective of the tests was to change the failure mechanism from concrete failure to steel failure with a targeted increase of the reinforcement ratio.

The different failure mechanisms observed for the tests on the horizontally lying shear connectors close to the edge corresponded to the failure types described in [1]. However, with regard to the load-carrying effect of the reinforcement, an additional failure of the concrete due to breakout between the reinforcement occurred (see Fig. 3). As a consequence of the selective arrangement of the reinforcement, the load-carrying capacity of the horizontally lying shear studs close to the edge under tensile loading was increased compared with the increase of the degree of reinforcement. The activation of the reinforcement was dependent on a sufficient overlap between the headed studs and the reinforcement as well as a sufficient anchorage length of the reinforcement in the theoretical concrete breakout cone (Fig. 6).

The tests demonstrated that the design approach according to the rules of composite construction in [3] is conservative because the geometric requirements according to Fig. 4 were not met, even for the tests with long headed studs with steel failure. Ductile load-carrying behaviour due to steel failure of the headed studs was observed in the tests with horizontally lying headed studs with two-sided edge influence, provided that the reinforcement was activated and concrete breakout between the reinforcement or bond failure of the reinforcement was not decisive.

The results of a numerical recalculation of the tests with MASA [16] are given in Fig. 7. A superposition of different failure mechanisms in the concrete can be observed (see Fig. 7 ① and ②). In addition to cracking due to the concrete breakout cone, cracking along the compression struts on the reinforcement occurred. Both failure mechanisms overlapped, especially when the anchorage length of the headed studs was short. For long headed studs, first a concrete breakout formed with the activation of the reinforcement (see Fig. 7 ③) before a breakout cone developed in the concrete.

The effect of the reinforcement can be understood very well on the basis of the numerical results in Fig. 7. In test R-01, for example, concrete failure can be observed between the reinforcement with a short embedment length and a low degree of reinforcement. The reinforcement stirrups are clearly stressed due to the compression strut development at the upper end of the stirrups. In test R-

Tab. 1 Test parameters of the studs under tensile loading

Test	Headed stud	Thickness of concrete plate [mm]	Supplementary reinforcement per headed stud [cm^2 per headed stud]	Concrete strength
R-01	SD 19/125	250	1.96 cm^2	C20/25
R-02	SD 19/125	250	3.93 cm^2	C20/25
R-03	SD 19/200	250	1.96 cm^2	C20/25
R-04	SD 19/200	250	3.93 cm^2	C20/25
R-05	SD 19/200	300	1.96 cm^2	C20/25
R-06	SD 19/200	300	3.93 cm^2	C20/25

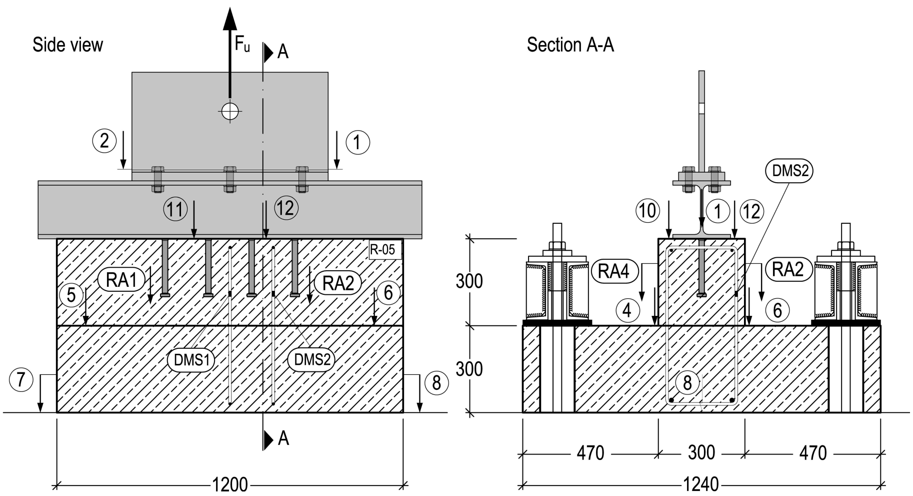


Fig. 5 Test setup of the studs under tensile loading

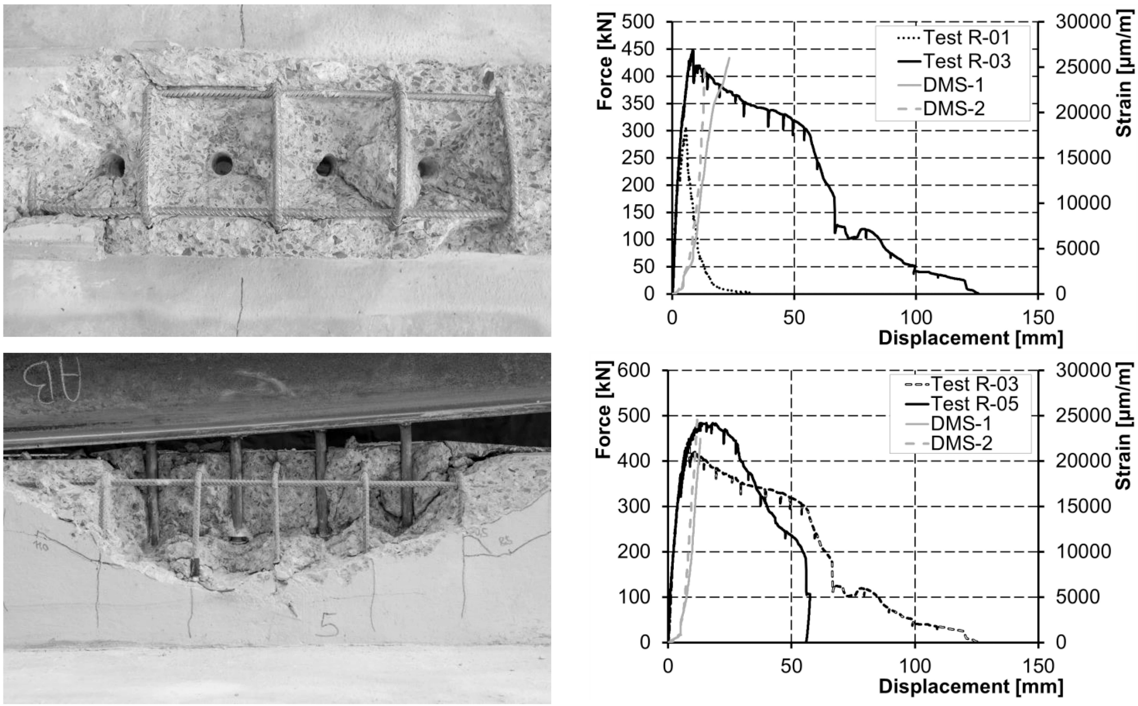


Fig. 6 Concrete breakout between reinforcement and load-deformation curve (top), concrete breakout with yielding of reinforcement and load-deformation curve (bottom), DMS = strain gauges

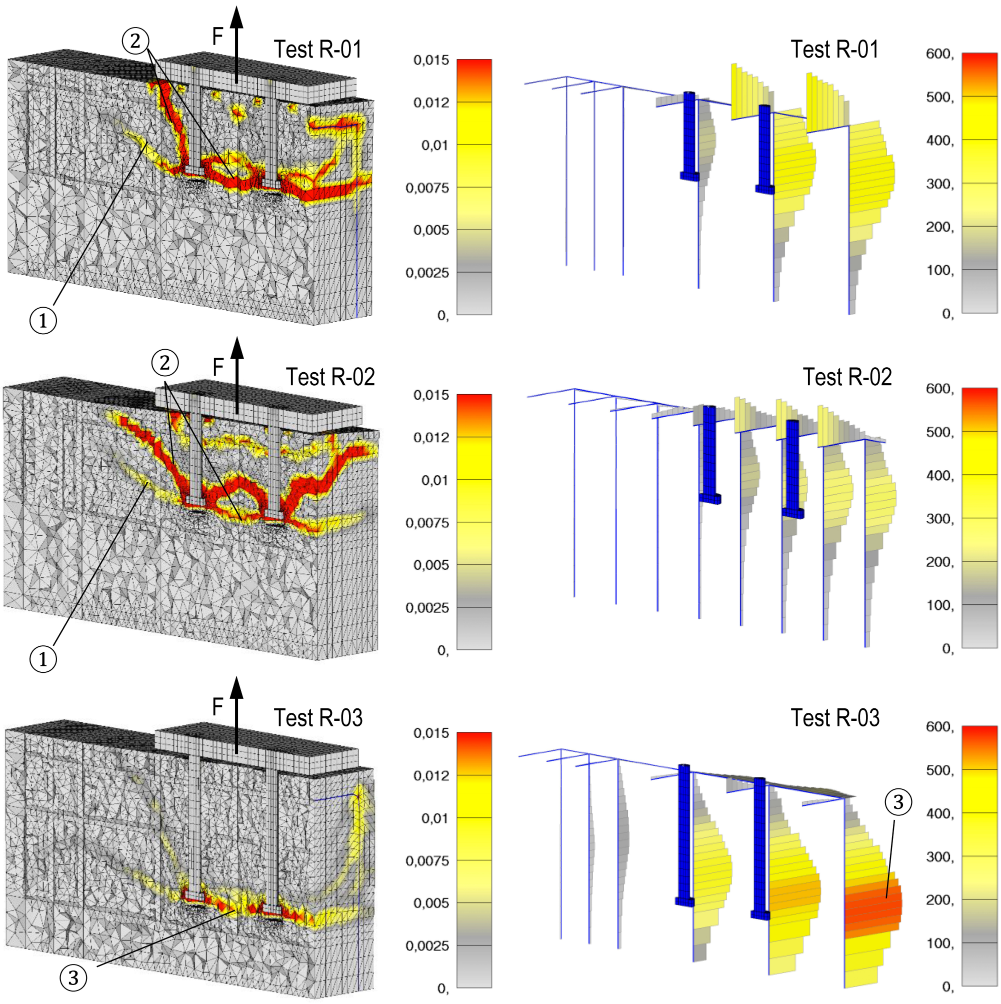


Fig. 7 Main tensile strains [–] (left) at maximum load and tensile stresses in the reinforcement [N/mm²] (right)

02 with a higher reinforcement ratio, the forces are distributed more evenly between the stirrups due to the closer stirrup arrangement and several rows of stirrups participate in the load transfer. In test R-03 with long headed studs, the reinforcement is activated up to yielding. The compression strut effect is rather small here.

3.3 Investigations on steel-to-concrete joints with concentrated loading

In steel-concrete composite construction, large loads often have to be transferred in a concentrated way into concrete (Fig. 8). Practical application examples are column bases or bridge bearings where, in addition to compressive forces due to a superimposed load, shear forces also have to be transferred into multi-edged concrete blocks. Concentrated load transfers also appear at two-edge supports or strip foundations.

The objective of the investigations was the development of an analytical model that allows the stirrup reinforcement already present in the concrete to be effectively considered in design. In the joints, the reinforcement was subjected not only to tensile or shear forces, but also to combined tensile and shear forces. Combined loading of the reinforcement by tensile and shear forces currently goes beyond the scope of EN 1992-4 [1] and was investigated in the experimental and numerical research programme [17].

The test specimens were designed in order to initiate failure of the concrete. The anchor plates were dimensioned with a sufficient thickness ($t = 30$ mm), so that a rigid load-distribution could be assumed in the tests. A test specimen geometry for a square column cross-section with an edge length of 35 cm, 40 cm and 60 cm was selected in the tests. With the aim of obtaining different failure mechanisms in the joint, the following parameters were varied in the test programme:

- Series 1: Small reinforcement ratio
- Series 2: High reinforcement ratio
- Series 3: Cracked concrete by crack induction
- Series 4: Short embedment length of headed studs
- Series 5: 3-row arrangement of the headed studs
- Series 6: Variation of the edge distance

Fig. 8 Damage to a concrete bearing block due to high shear force loading

Within the series, parameters such as the number of edges of the test specimens (two- or four-sided), the support of the test specimens at the load application plane (fixed or free), and the material strengths of the headed studs and the concrete were also varied. The parameters of the test programme were varied in such a way that the results could directly be compared with each other by varying only one parameter at a time. The test specimen was anchored to the strong floor by cross girders (Fig. 9). The load was applied eccentrically ($e = 100$ mm) via the tension lugs at the anchor plate.

In practice, joints with concentrated load application are usually compressed by a superimposed load. By fixing the anchor plate via a compression block (see Fig. 9a), it was possible on one hand to create this load situation due to the reaction forces during the test, and on the other hand to investigate pure shear force loading of the joint without any fixing (see Fig. 9b). With the fixation of the anchor plate, significant increases in ultimate load were possible (Fig. 10) because pry-out failure of the anchor plate on the side opposite to the load was prevented and frictional forces were activated via the reaction forces. Due to the eccentric load application ($e = 100$ mm), concrete breakout was observed on the opposite side of the load in the tests without fixation, which meant that the full shear force carrying capacity was not achieved (see test B1-2 in Fig. 10). The failure mechanisms under shear load perpendicular to the edge of the concrete block, with concrete edge failure starting from both rows of headed studs, were comparable in the tests with and without fixation. Frictional forces could also be transmitted in the tests with small edge distance. Despite the concrete edge failure, starting from the rows of headed studs, a compression surface formed in the centre of the joint between the anchor plate and the concrete, through which frictional forces could be transmitted even when the concrete failure cone was formed.

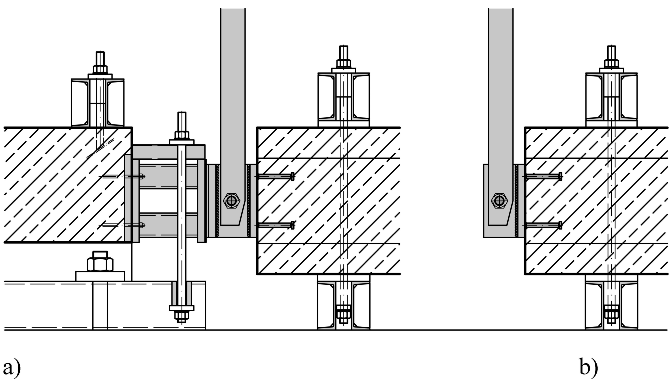


Fig. 9 Compression block for fixing the anchor plate (a) and test without fixing (b)

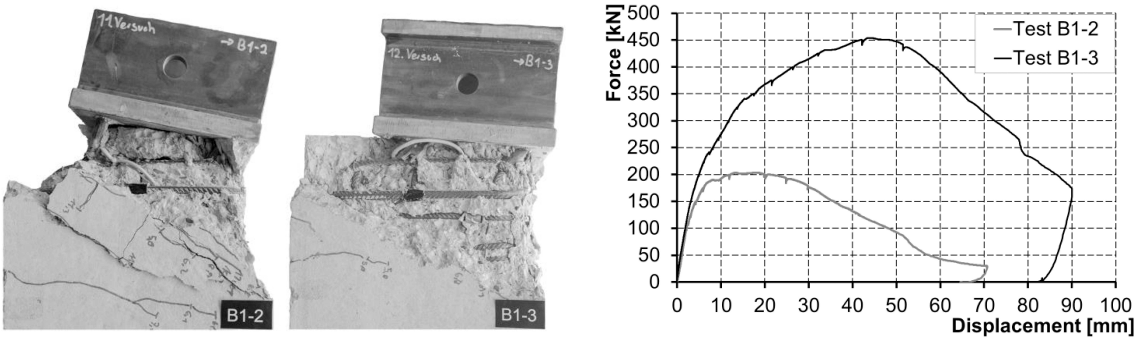
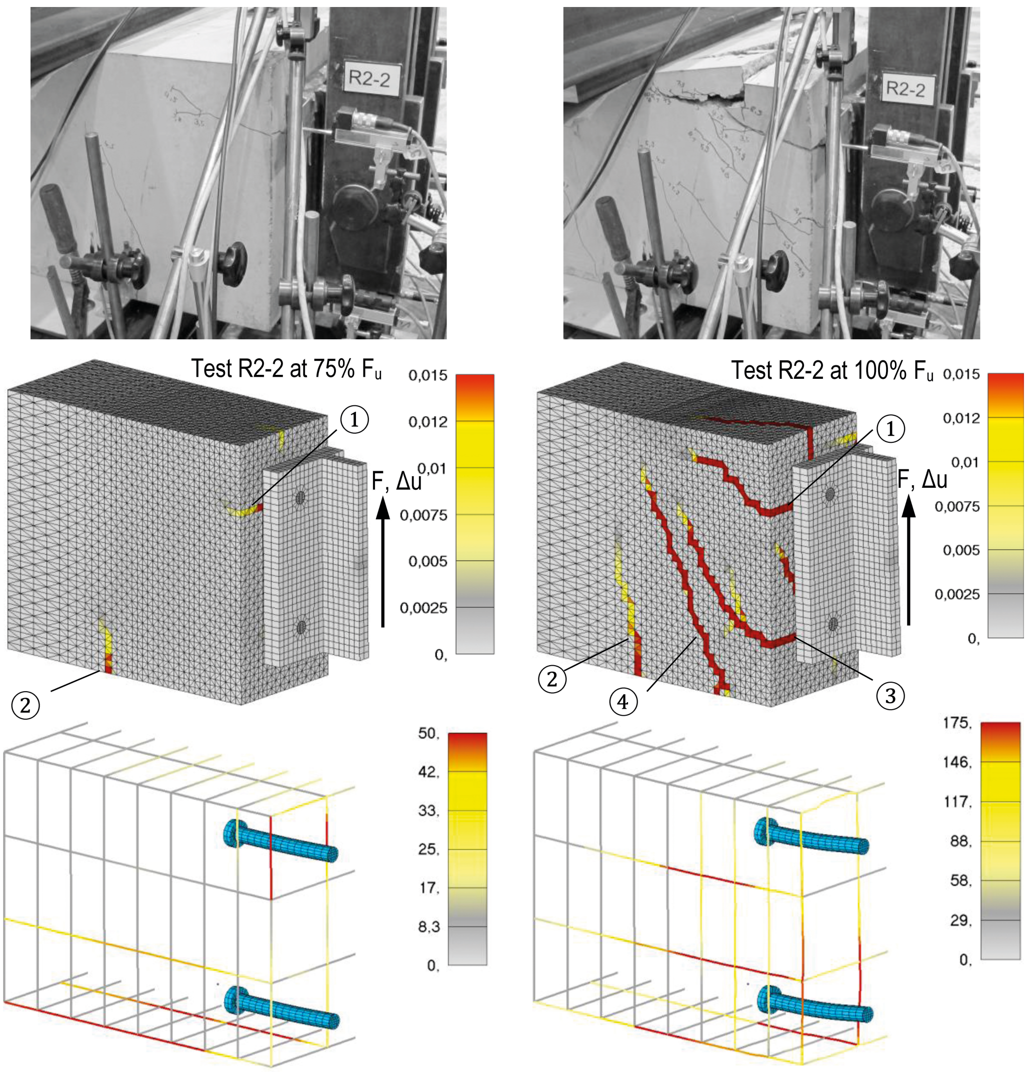


Fig. 10 Failure of test B1-2 without superimposed load (left) and test B1-3 with superimposed load (right) and comparison of the load-deformation curves

Figure 11 shows the results of the recalculation of the test R2-2 without fixation and four edges. With concrete edge failure starting from the row close to the edge (Fig. 11 ①), the shear forces are transferred to the row far from the edge (Fig. 11 ③). In addition to the bending cracks in the concrete cross-section, Fig. 11 ② outside of the anchorage zone, the eccentric load application causes a concrete failure due to the tensile stress of the headed stud row (Fig. 11 ④). In the joint, the failure mechanisms partially overlap and thus favour each other. The shear force redistribution and the activation of the reinforcement in tension at the anchor plate at the unloaded side can be understood from the stress diagrams of the reinforcement shown in Fig. 11. In the tests with four-sided edge influence, a load redistribution of the shear forces is already observed from approx. 50 % of the maximum load, while in the joints with only two-sided edge influence an addi-



a) b)

Fig. 11 Crack development and reinforcement activation in test R2-2 at 75 % of the load (a) and at maximum load (b) tional increase in the ultimate load due to the activation of the concrete at the sides occurs.

As the concrete becomes more damaged, the shear forces are redistributed to the studs row further away from the edge and the reinforcement is activated on the side opposite from the load. For joints with four-sided edge influence, a smaller ratio of reinforcement stirrups can be activated under transverse load due to the concrete edges. However, higher ultimate loads can be achieved in the tensile area than in the tests with two-sided edge influence due to the additional reinforcement stirrups on the sides. The results of the numerical investigations show that, for the given geometries, the concrete cross-section is completely cracked when the maximum load is reached and no simultaneous load-carrying effect of reinforcement and concrete is present.

In the tested joints, the anchor plate was sufficiently rigid due to the load introduction welded directly over the headed stud, so that load redistributions due to a yielding behaviour of the anchor plates were excluded. With the experimental and numerical investigations, the load-carrying behaviour of the joints with concentrated loading in the area close to the edge was recorded and requirements for a possible analytical verification model determined. Due to the high degree of reinforcement, tensile forces were transmitted even in case of damage in the area close to the edge.

The shear force distribution between the rows of headed studs was dependent on parameters such as edge spacing and fixation. With small edge distances, a load redistribution to the row far from the edge took place. In the tests with large edge spacings, it was observed that the row close to the edge transferred a larger proportion of shear force, since the pry-out of the anchor plate on the opposite side resulted in lower stiffness and a smaller proportion of shear forces was carried.

The experimental and numerical investigations showed that even with small edge distances, a load-carrying capacity can be assigned to the headed stud row close to the edge in the cracked state, an effect considered in the derivation of an analytical model. In the case of a concrete edge failure starting from the row near the edge, frictional forces were activated in the joint. The background to this was that the contact area between the anchor plate and the concrete shifted to the middle of the joint, since the area near the edge did no longer any load transfer.

For the joints in concrete members with two-sided edge influence, a common load-carrying effect of reinforcement and concrete under tensile and shear forces was observed. The reinforcement stirrups located further away from the anchor plate were gradually activated with the continuous cracking. For joints with four-sided edge influence, only a small combined load-carrying effect of reinforcement and concrete was observed, as the concrete was completely cracked.

Fixation has a significant influence on the load-carrying behaviour of the joints. As lifting of the anchor plate in tension is prevented, additional stiffness is generated with the fixation and increase of the ultimate loads. For the derivation of the analytical model, it is proposed to distinguish between different states of crack development and force ratios, e. g., after formation of the concrete edge failure in the concrete. In this way, both, close to the edge and far-edged anchor plates, are considered.

4 Development of design models for the joints based on the component method

4.1 General

In the following, major aspects of the development the models based on the component method are presented for the joints with headed studs close to the edge and the joints with concentrated loading. A detailed description of all models is given in [6]. Possible failure mechanisms in the area of the joint are identified based on the experimental and numerical studies for the individual components, and models are proposed to calculate the resistances of the overall joint. The internal forces acting on the joint are analysed in terms of fastening technique by resolving them into resultant normal and shear forces at the fastener level and then comparing them with the resistances of the individual components.

In the following, the individual components are described with a focus on the maximum load-carrying capacity, which is decisive for determining the total load-carrying capacity of the joint. These components are also based on stiffness relationships with regard to a deformation-based calculation, which were developed for concrete components for the first time in [5]. In particular for the combined load-carrying capacity between reinforcement and concrete, the description of the load-deformation relationships is an important component for estimating the load-carrying capacity of concrete and reinforcement.

The component with the lowest load-carrying capacity is decisive for the design of the joint. In this way, the joint can be designed by specifically dimensioning these structural components with the relevant parameters, such as reinforcement diameter, concrete strength and anchorage length.

4.2 Analytical model for the joints with horizontally lying headed studs close to the edge

A condition for the development of the model is a rigid, equal introduction of the forces into the headed studs. The model is developed primarily for failure of the horizontally lying shear studs close to the edge in the concrete, so that failure at the steel, the load introduction or the anchor plate is not considered in the following. The observations on the bearing behaviour of the experimental and numerical investigations of horizontally lying shear studs close to the edge are used as a basis for the derivation of the analytical model. This requires a two-step approach for the verification of the experimental results and the model development of headed studs in a theoretically unlimited linear arrangement in a composite beam.

For single failure mechanisms such as steel failure of the headed stud shaft or pull-out, a resistance can be directly assigned in a first step to a single headed stud and the model reproduces the application of horizontally lying shear studs close to the edge with linear arrangement with sufficient accuracy. In the case of group failure mechanisms such as concrete breakout with activation of the reinforcement lying in the breakout cone, there are differences in the load-carrying behaviour between a joint with a limited number of headed studs and with theoretically unlimited headed studs arranged in series that are considered in a second step. The load-carrying capacity of the horizontally lying shear studs close to the edge is determined for both application situations by the governing individual component with the lowest resistance according to Fig. 12.

For joints with a short overlap length between the reinforcement and the anchorage length of the headed studs and with a large distance between the reinforcement and the headed studs, the resistance to concrete breakout between the reinforcement decreases because the compression strut inclination becomes more flat and, as a result, the tensile stress in the cracked zone increases (see Fig. 7). A semi-empirical engineering model [5] exists for concrete breakout between reinforcement, which may be used to capture these influences. The positive support effect of the reinforcement is taken into account in Eq. (2) by the coefficient ψ_{supp} according to Eq. (3). For the coefficient ψ_{supp}, a simplifying linear relationship is proposed for joints between steel and concrete.

$$N_{u,cs} = \psi_{supp} \cdot N_{u,c} \leq N_{u,re} \ [N] \tag{2}$$

$$\psi_{supp} = A - B \cdot \frac{x}{h_{ef}} \geq 1.0 \tag{3}$$

where:

$N_{u,c}$ is the resistance for concrete failure [N];
$N_{u,re}$ is the resistance to steel or bond failure of the reinforcement in the case of common load-carrying action with the concrete [N];
ψ_{supp} is the factor to consider the positive support effect of the reinforcement with $A = 2.5$ and $B = 1.0$ [−];
x is the radius of the developing breakout cone taking into account the existing reinforcement assuming crack development of the breakout cone with an inclination of 35° (see Fig. 4) [mm];
h_{ef} is the effective anchorage depth [mm].

In accordance with the approach for concrete breakout between the reinforcement in beam-shaped reinforced concrete elements according to [17], a calculation of the resistance $N_{u,cs}$ is carried out for the core area $A^1_{c,N}$ and the lateral areas $A^2_{c,N}$ according to Fig. 13. The headed studs are not only supported by the nearby stirrups, but in the case of a close reinforcement layout, compression struts also form on rows of stirrups further away. Since

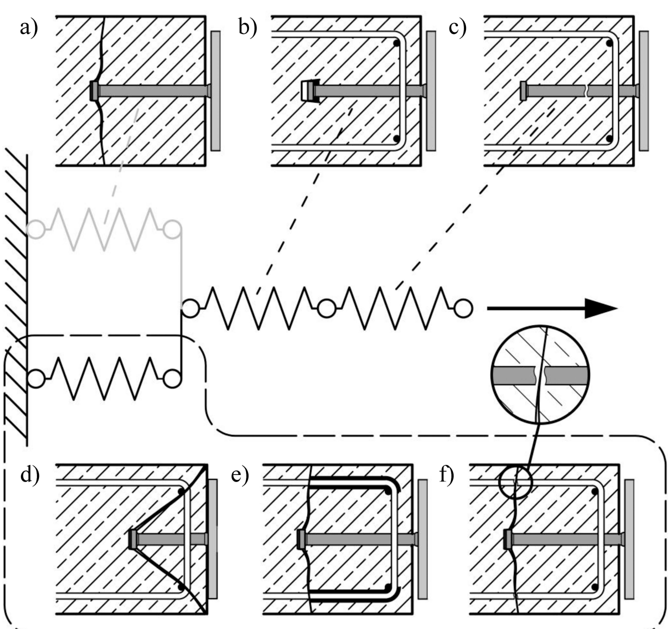


Fig. 12 Analytical model for an horizontally headed stud close to the edge with a) concrete breakout; b) pull-out failure; c) steel failure of the headed stud; d) concrete breakout between the reinforcement; e) bond failure of the reinforcement; f) steel failure of the reinforcement

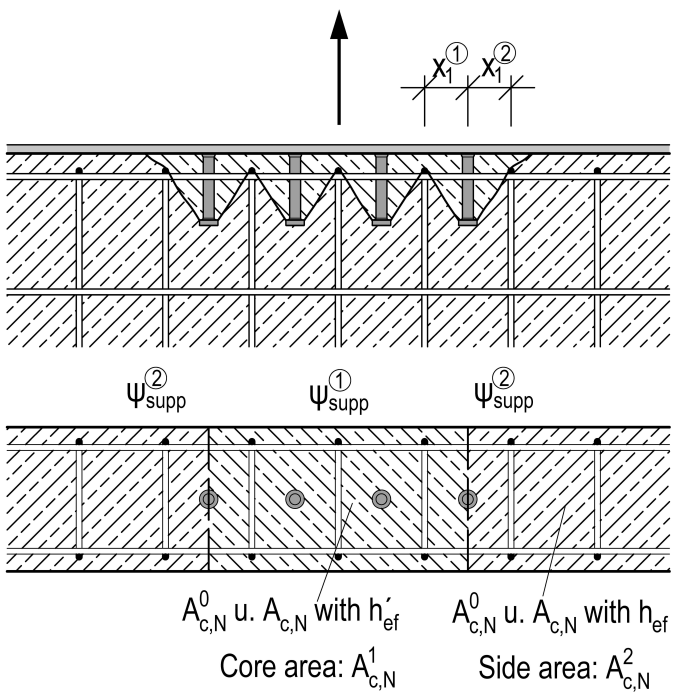


Fig. 13 Concrete breakout between the reinforcement of the horizontally lying shear studs close to the edge

this effect is particularly noticeable in the core area, an adjustment of the factor ψ_{supp} according to Eq. (3) with $A = 4$ and $B = 3.3$ is proposed for this area. In addition, the distance x_1 is to be applied for both areas according to Fig. 13.

From the validation of the model by the tests (Fig. 14), the conclusion can be drawn that the approaches for the load transfer of reinforcement and concrete according to [4] and [5] are suitable, with modifications, for estimating the load-carrying behaviour of the joints with reinforcement. It should be taken into account that the existing models for the common load-carrying effect of reinforcement and concrete were developed for joints in the area far from the edge and, therefore, adjustments have to be made when applying the calculation approaches for situations close to the edge. The analytical model was also validated on the numerical parametrical investigations of the dissertation [8]. The maximum loads can be determined with sufficient accuracy using the model for concrete compressive strength classes between C20/25 and C50/60 and varying the reinforcement from Ø 8 mm to Ø 20 mm.

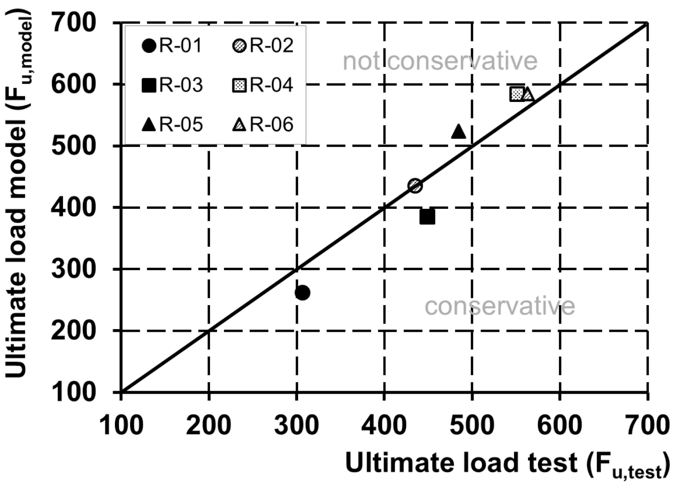
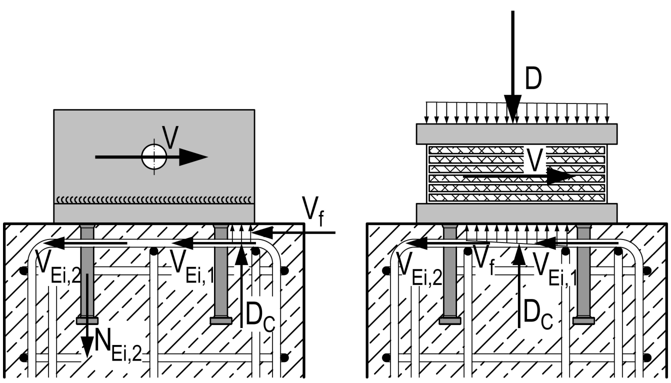


Fig. 14 Validation of the analytical model for the horizontally lying studs close to the edge by the test results



a)

b)

Fig. 15 Analytical model for joints with eccentric shear load (a) and for joints under shear and compression load (b)

4.3 Analytical model for joints with concentrated loading

In addition to the design of the joints in terms of load-carrying capacity, the design process can use the split of the joint into individual components to design the joints in such a way that a ductile failure becomes decisive. For the joints with concentrated loading with and without superimposed load, models according to Fig. 15 are proposed. The result of the experimental and numerical investigations was that load redistributions take place in the joints with concentrated loading depending on the damage behaviour in the area near the concrete edges. This redistribution is captured by the analytical model.

In case of a shear load perpendicular to the edge of the structural member, the concrete usually fails starting from the front row of headed studs and the shear forces are redistributed to the rows of headed studs far from the edge. Failure of the joint in the area close to the edges occurs when, after load redistribution in the far-edged row, the maximum possible utilisation factor for steel or concrete failure is reached. In accordance with the experimental observations, a mixed failure is also possible, for example, with a bond failure of the reinforcement starting from the row close to the edge and a steel failure due to shearing of the headed studs on the far-edged side (Fig. 16).

In state I, the shear forces are distributed equally between the rows of headed studs, since the same stiffness is assumed for all rows. With the formation of cracks starting from the front row of headed studs, the forces are redistributed and the row of headed studs far from the edge becomes decisive for the failure of the joint in condition II (Fig. 17). With the complete load redistribu-

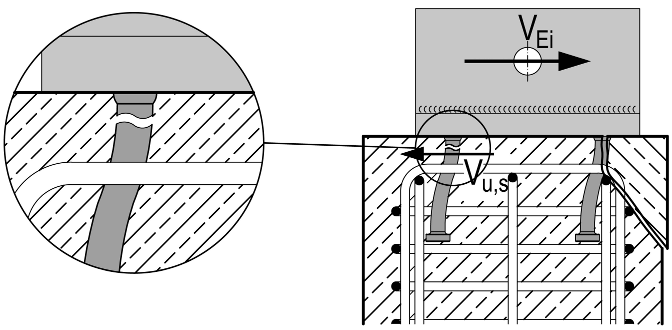


Fig. 16 Combined concrete and steel failure due to load redistribution in the joint

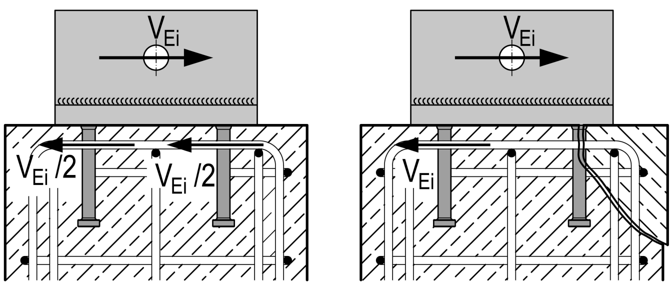


Fig. 17 Load distribution of shear forces in state I (a) and state II (b)

tion of the shear forces to the row far from the edge, a safe estimate is proposed within the model.

The combined load-carrying effect of reinforcement and concrete is assumed according to [17] for two-sided edge influence. A deformation-based approach is assumed for the tensile area, in which the ultimate load of the reinforcement component is reduced in function of the deformations at maximum load. For the joints with four-sided edge influence and small edge distances, it can be assumed that with the activation of the reinforcement, the concrete cross-section is completely cracked and a combined load-carrying effect is not possible.

The validation of the analytical model for the tests with concentrated load application was carried out by comparing the calculated and experimental maximum loads and with regard to the governing failure mechanism by taking the governing interaction relationship into account. With the formation of a concrete edge failure starting from the row closed to the edge, the forces were assumed to redistribute to the nearest highest-loaded row. With combined tension and shear loading, steel failure was considered possible in the headed studs under tension and shear. For joints with sufficient edge distance, composite failure under tension in combination with concrete pry-out failure should be considered.

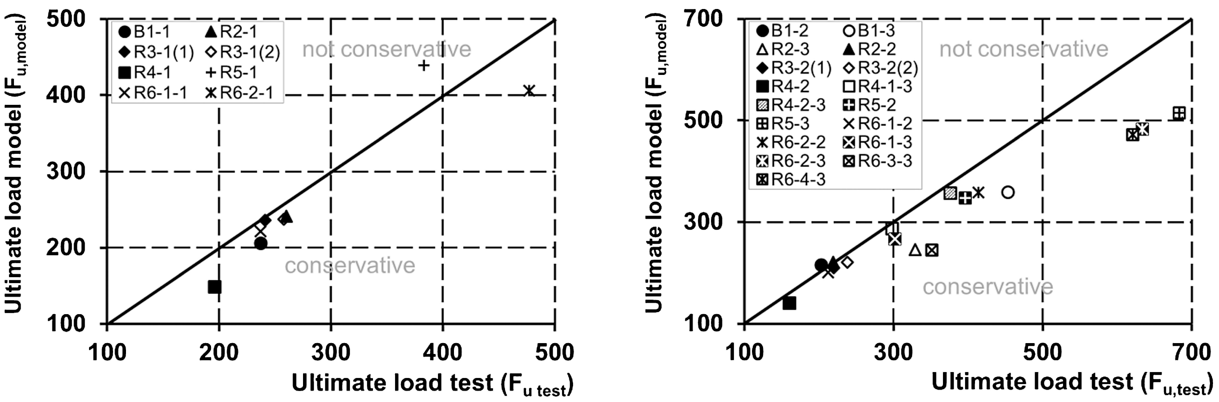
The resistances of the single components were calculated at ultimate load level using the experimentally determined material properties. The individual components were usually considered unchanged and, for example, for the special application for the joints with concentrated load application, no additional ψ coefficients were defined, e.g., to take into account the effectiveness of the different stirrup rows. With the component model based on the fastening technology [1], a sufficient agreement of the experimental and analytical ultimate loads of the joints with two- and four-sided edge influence was achieved with $F_{u,Model}/F_{u,Test} = 0.97$ at a coefficient of variation of $\upsilon \approx 13.1\,\%$ (Fig. 18).

4.4 Verification of the analytical model, derivation of a design model and normative implementation

The analytical model was derived on the basis of the average resistances of the individual components under normal and shear loads. For the derivation of a design proposal, model uncertainties such as scatter of different parameters were evaluated. This included the consideration of possible variabilities of the model parameters, such as the material parameters or the geometric dimensions. In addition to the statistical evaluation of the test results within the defined groups, upper bounds were derived at a characteristic level (Fig. 19). Taking into account the given resistances of the individual components, the design resistances of the analytical model were below the limit values according to EN 1990 Annex D [18].

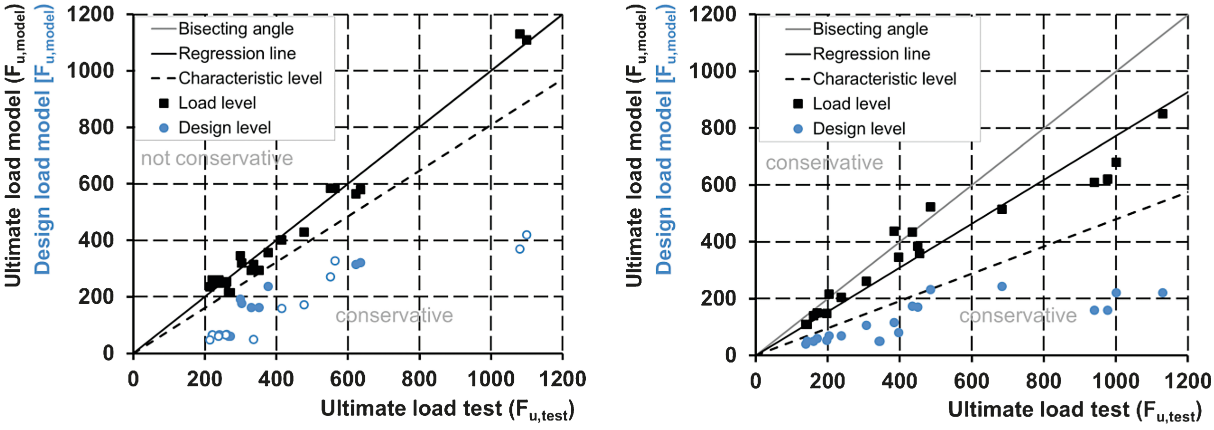
In the analytical model, sufficient agreement was achieved between the medium ultimate loads and the experimental maximum loads for identical failure mechanisms. An exception was formed by the investigations on large anchor plates with small eccentricities, where the ultimate loads at concrete failure were clearly underestimated with the previous models. In addition, in the recalculation of the test results at design-level, the larger scatter range of the concrete affects the failure modes. While for the concrete failure mechanisms at the tests theoretical concrete failure became decisive also at design level, for the tests with a steel failure theoretical concrete failure mechanisms were decisive due to the more conservative resistance models and the more stringent requirements for the partial factors (see Fig. 19).

During the revision of the Eurocodes under Mandate M/515 [20], a modification was developed for the new concrete components which was implemented in the new draft of FprEN 1993-1-8 [19] in a concise form. In detail, this means that in the current draft, the joints between steel and concrete with fasteners are listed in Annex D.4 of [19] with reference to fasteners between steel and concrete in accordance with [1]. The allowance to consider the reinforcement using suitable verification models, such as those shown above, is explicitly given in the form



a) b)

Fig. 18 Comparison of the analytical model with the maximum loads of the tests with two-sided edge influence (a) and with four-sided edge influence (b)



a) b)

Fig. 19 Evaluation of the analytic model with steel failure of the headed studs (a) and with concrete failure (b) with evaluation according to EN 1990 Annex D [18]

of an opening clause for the tensile components in Chapter A.19 of the new draft of [19].

5 Conclusions and outlook

In this article, verification models for practical applications of joints between steel and concrete and their background were explained, derived within [8]. The models can be used to determine the load-carrying capacity of the joints by integrating existing concrete components according to EN 1992-4 [1] as well as more recent approaches into the concept of the component method according to EN 1993-1-8 [2]. The analytical model presented in the article can be used to consider different loading situations such as horizontally lying studs close to the edge under tension loading, anchor plates for shear loading or column bases or bearings under normal force and shear loading. It was shown that the component method can be used to capture the different failure mechanisms in steel and concrete in the joint. The model development for joints between steel and concrete was based on more than 45 own component tests. The application situations investigated have in common that the load-carrying behaviour of the joints is influenced by the reinforcement present. Based on the experimental investigations, extensive numerical investigations were carried out, e. g., on the load-carrying effect and activation of the reinforcement, for the derivation of suitable verification models, and the data base for the validation of the analytical model was expanded.

The analytical models developed at ultimate load level, e. g., taking into account the experimental steel and concrete strength, were transferred to the design level and the reliability was evaluated according to EN 1990 Annex D [18]. The result of this evaluation was that the joints investigated can be designed on the basis of the existing characteristic design of EN 1992-4 and EN 1993-1-8. First steps were undertaken for an implementation of the new approaches in FprEN 1993-1-8 [19], the relevant draft of the second generation of Eurocodes [20].

The topic of joints in steel and composite structures has been dealt within several research projects and dissertations at the Institute of Structural Design of the University Stuttgart, which are also based on a close cooperation with the Department of Fastening and Strengthening Methods of the Institute of Construction Materials (IWB) of the University of Stuttgart. Based on the joints presented here, further research projects have been derived, which, for example, specifically investigate issues related to the influence of the imposed load on anchor plates [21] and the fatigue strength of headed studs [22]. The consistent research in this area is thus the appropriate answer to questions from practice in the field of steel-to-concrete joints.

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