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Bearing capacity of headed studs under combined tension and shear loading in composite beams with large web openings

Manuel Risch[1] | W. Kurz[1] | K. Wolters[2] | T. Janiak[2] | G. Christou[2]

Correspondence

Manuel Risch M. Sc.
University of Kaiserslautern-Landau, Germany
Erwin-Schrödinger-Straße 52
67663 Kaiserslautern
Email: Manuel.Risch@RPTU.de

[1] University of Kaiserslautern-Landau, Germany
[2] RWTH Aachen University, Germany

Abstract

The use of steel-concrete composite structures with a high installation grade is becoming increasingly popular in building and industrial construction. To reduce construction height building services are routed through web openings in the girders. However, these openings represent local points of interference where, in the case of composite girders, parts of the acting shear forces are transferred from the web of the steel profile into the concrete slab. This results in additional, local stresses in the remaining steel girder and in the concrete chord, which must be considered in the design of the floor girders and shear connectors. Web openings in composite girders are not addressed in the current European design standard for steel-concrete composite construction (EC 4). Only with the introduction of the second generation of Eurocodes in the coming years this case will be normatively regulated. During the preparation of the standard further questions about the load-bearing behaviour arose, as the existing design approaches usually only consider a selection of possible failure scenarios or neglect essential verification steps. A joint research project between the University of Kaiserslautern-Landau and RWTH Aachen University aims to develop a suitable design concept for composite girders with web openings. Model and beam tests accompanied by numerical simulations will provide further information on the complex local and global load-bearing behaviour of the composite girders.

This paper presents the results of experimental investigations and numerical simulations on the influence of large web openings on the global load-bearing behaviour of the shear connectors in the composite joint. Based on 60 pull-out tests and numerical simulations, the load-bearing behavior of head bolt anchors under combined shear and tensile loading was researched and evaluated.

Keywords

Composite Beams, Web openings, Design Approach, Shear Connectors

1 Introduction

In modern buildings with a high installation grade, beams with large web openings are used more and more often. The installation can be laid parallel to the span direction of the girders with hardly any problems. When crossing the direction of alignment or the installations must be routed through web openings in the composite girders. However, web openings then represent local interference points. In the case of composite girders, part of the acting shear force is transferred from the web of the steel section into the concrete slab, if the slab provides significant stiffness [1, 2]. Contact pressure between the concrete chord and the top flange of the steel girder at the edge with lower bending moments introduces the transverse force into the concrete chord, while the shear force is returned to the steel girder on the opposite edge through tensile forces in the shear connectors. Those shear connectors must transmit tensile forces in addition to their longitudinal shear loads (cf. Figure 1).

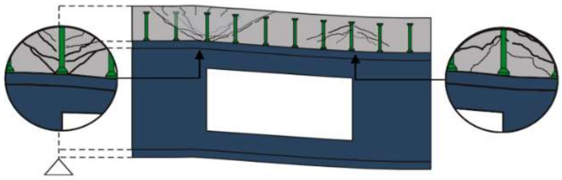

Figure 1 Load-bearing behaviour of headed studs at the opening

The influence of this interaction of shear and tensile forces at an opening edge must be investigated by means of numerical simulations and small-part tests. Numerical simulations are mainly used to estimate the ratio of the force

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to be transmitted as a function of the tensile force. In contrast, the actual load bearing, and deformation capacity of the shear connectors is to be investigated by component tests.

2 Load-bearing behaviour of the shear connectors in the opening area

Numerical simulations and laboratory tests are suitable for investigating the load-deformation behaviour of the shear connectors around large web openings. The numerical simulations are useful for first estimating the load-bearing behaviour. The actual load-bearing behaviour can then be determined by the laboratory tests. Finally, the numerical simulations can be calibrated on the laboratory tests to carry out parameter studies.

2.1 Numerical Simulations

To understand the complex behaviour of composite beams with large web openings, numerical simulations were performed using Abaqus® FEM software. For this purpose, data from previously conducted beam tests from Weil [3] were used to calibrate the numerical models on real girder tests. Both the steel girder with headed studs and the concrete chord were modelled as solid elements. The reinforcement was embedded in the concrete slab by using beam elements (B31). The material properties were determined based on accompanying specimens and mapped by means of elastic-plastic stress-strain relationships. To capture the brittle material behaviour of the concrete, the Concrete Damaged Plasticity Model (CDP) was used. As plasticity parameters the following values were used: Dilation angle= 37°, eccentricity= 0.1, f_{b0}/f_{c0}= 1.16 and K_c= 0,55. The material behaviour of the headed studs and the steel section is represented as a multilinear stress-strain relationship. The reinforcement on the other hand, is modelled bilinearly. The discretization was based on hexagonal elements (C3D8R). An edge length of 10 mm was chosen as the size for the elements. The examination of the component was carried out dynamically explicit. To reduce the calculation time, a mass scaling of 30 is used. A section of the girder with web opening together with the decisive headed studs is shown in Figure 2.

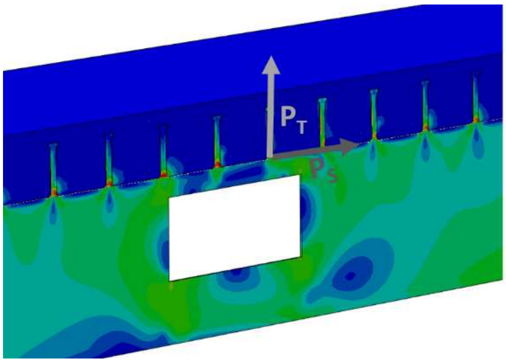

Figure 2 Composite girder and decisive headed studs

Looking at the stresses of the decisive headed studs separately in shear forces P_S and in tensile forces P_T based on Figure 3, different ratios for P_T/P_S result with increasing load levels. In this specific case, the ratio of tensile stress to shear stress lies between 0.34 and 2.95 for the headed stud at the right-hand edge of the opening. Due to the lack of information on the tension-shear interaction for headed studs in solid and composite slabs, it is advisable to investigate this load-bearing behaviour in more detail by means of experimental investigations.

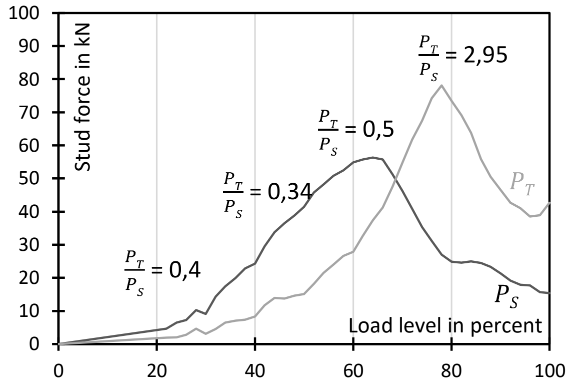

Figure 3 P_T/P_S ratios for a headed stud in the web opening area

2.2 Experimental Investigations

To investigate the load bearing and deformation behaviour of headed studs under combined shear and tensile loads (cf. Figure 1), a series of tests is carried out regarding the load-bearing capacity of headed studs under combined tension-shear loading. The subject of the tests was both solid and composite slabs loaded under 5 different load angles from 0° (pure tension) to 90° (pure shear). To guarantee the widest possible range of applications three different steel sheet geometries were used. The composite sheet types investigated were a re-entrant profile (SHR51), a modern shaped profile with stiffener (Cofraplus 80) and a trapezoidal profile (Cofraplus60). In all tests, except for the trapezoidal sheets, headed studs with a diameter of 22 mm and a height of 125 mm were used. For the trapezoidal sheets headed studs with a diameter of 19 mm and a height of 100 mm were used. The distance between the headed studs was based on the respective composite sheets with one headed stud per trough. The spacing in the solid ceiling was chosen to be the same as the spacing of the re-entrant profile with 150mm. For all specimens, the dimension of the concrete slab is 1000 mm in longitudinal direction of the steel girder and 850 mm in transverse direction. The thickness of the concrete slab was about 140 mm for the specimens with trapezoidal sheets and 160 mm for the remaining specimens. The concrete grade class was scheduled as C30/37.

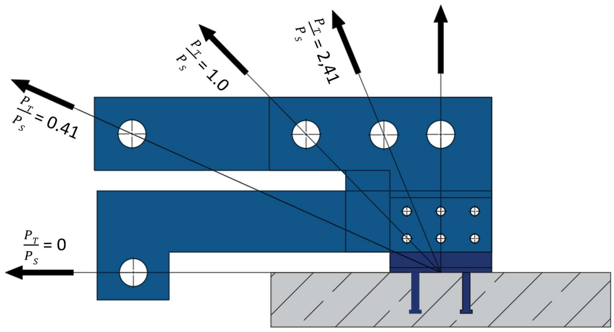

Figure 4 Load introduction to reduce the misalignment moment.

The investigated tension-shear ratios were achieved by installing the test specimens in a specially designed test rig aligned at the appropriate angle to the test cylinder. Individual load application concepts for each load angle, analogous to [1], ensured that the test load was applied to the headed studs without misalignment torque (cf. Figure 4).

The deformations of the specimens are measured by several LVDT`s. At the respective corners of the steel profile, the slip between steel profile and concrete slab was measured parallel to the longitudinal axis of the beam. The relative transverse separation between steel profile and concrete slab was measured as close as possible to each headed stud, perpendicular to the load angle. For the solid slabs it was measured on the concrete surface and for the composite slabs on the surface of the metal sheet.

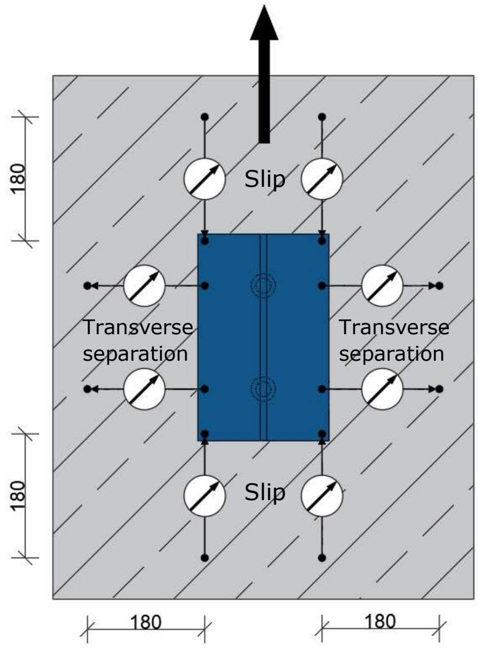

Figure 5 Instrumentation plan for the pull-out-tests

All specimens were loaded according to prEN 1994-1-1 [4], Annex B. First, the specimens were cyclically preloaded by means of 25 load cycles between 5 and 40 percent of the expected failure load. Subsequently, the load was increased stepwise until the ultimate load was reached. Testing was stopped at several load level to investigate short-term relaxation (cf. Figure 6).

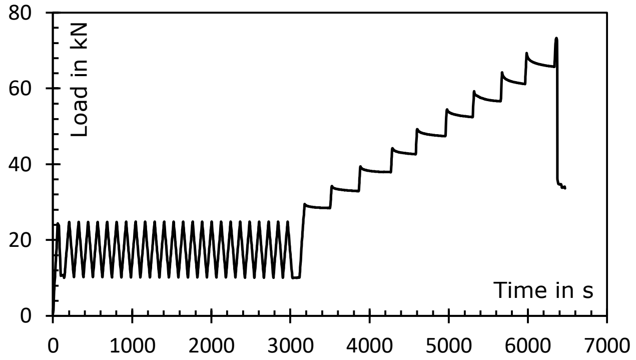

Figure 6 Loading procedure of the pull-out-tests.

The concrete properties are determined for at least 6 concrete cylinders with a height of 300 mm and a diameter of 150 mm. The mean compressive strengths f_{cm} per series are in a range between 23.3 and 45.6 N/mm² with a maximum coefficient of variation of about 0.1. For the tensile strength f_{ctm}, the mean value is between 1.8 and 2.8 N/mm² with a maximum coefficient of variation of 0.14. The individual concrete properties are listed in the following Table 1.

Table 1 Concrete properties of the different test series

P_T/P_S	f_{cm} [N/mm²]	Cov [-]	f_{ctm} [N/mm²]	Cov [-]
0	23.3	0.10	1.8	0.07
0,41	42.0	0.05	2.8	0.11
1	36.5	0.06	2.6	0.14
2,41	45.6	0.05	2.8	0.12
/	35.2	0.06	2.4	0.12

The graphs shown below represent the mean values of the shear force-slip relationships determined from 3 individual tests. The load-deformation behaviour of the solid and composite slabs is given depending on the ratio of tensile stress to shear stress. P_T/P_S= 0 corresponds to a pure shear load and P_T/P_S= 2.41 to an inclination of the specimen to the horizontal by 22.5° (cf. Figure 4). In addition, the diagrams contain a schematic illustration of the tested slab geometry and a detailed view of the P_T/P_S ratios of 1 and 2.41 at low slip ratios. The evaluation of the test results in Tables 2 to 4 is carried out according to prEN 1994-1-1 Annex B [4] and DIN EN 1990 Annex D [5] separately for each specimen constellation and each P_T/P_S ratio.

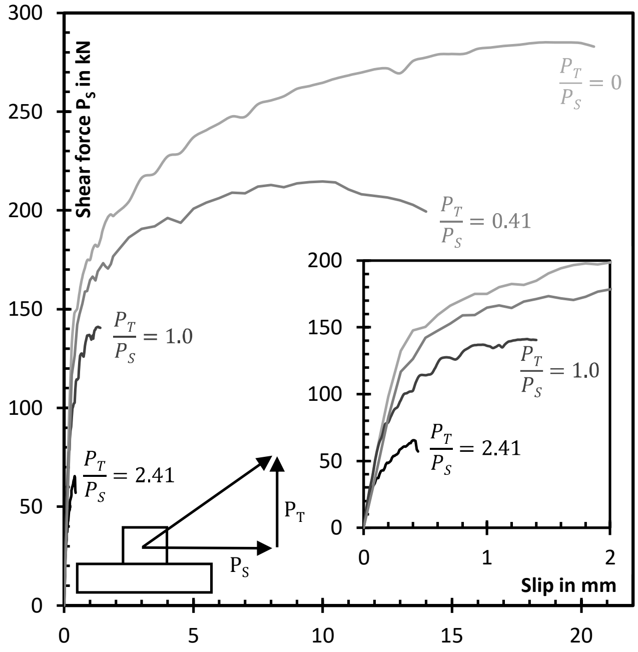

Figure 7 Shear deflection behaviour of solid slabs

For a ratio of P_T/P_S= 0, the characteristic load per headed stud P_{Rk} for the solid slabs is 119.1 kN with a characteristic slip δ_{uk} value of 18.68 mm (Figure 7). As the ratio of vertical to longitudinal load increases, the shear load, and the associated slip decrease. The characteristic slip capacity of the slabs with a load ratio of 0.41 cannot be determined due to the high scatter in the individual tests and a resulting low P_{Rk} of about 80.5 kN. With a P_T/P_S ratio of 2.41, the characteristic shear capacity and characteristic slip of a single stud decrease to 28.4 kN and 0.38 mm.

Table 2 Test evaluation of the solid slab tests per headed stud

P_T/P_S	P_e [kN]	Cov [-]	P_{Rk} [kN]	δ_{ek} [mm]	δ_{uk} [mm]
0	142.9	0.10	119.1	1.02	18.68
0.41	108.4	0.15	80.5	0.40	/
1	71.8	0.04	61.0	0.40	1.19
2.41	33.1	0.08	28.4	0.20	0.38

The composite slabs with a re-entrant steel sheet in Figure 8 show a similar behaviour to the solid slabs. Here, the shear capacity and slip also decrease with an increasing proportion of tensile force. In this case, the results of the tests under pure shear loading could not be reproduced because the test setup was improperly modified for this constellation.

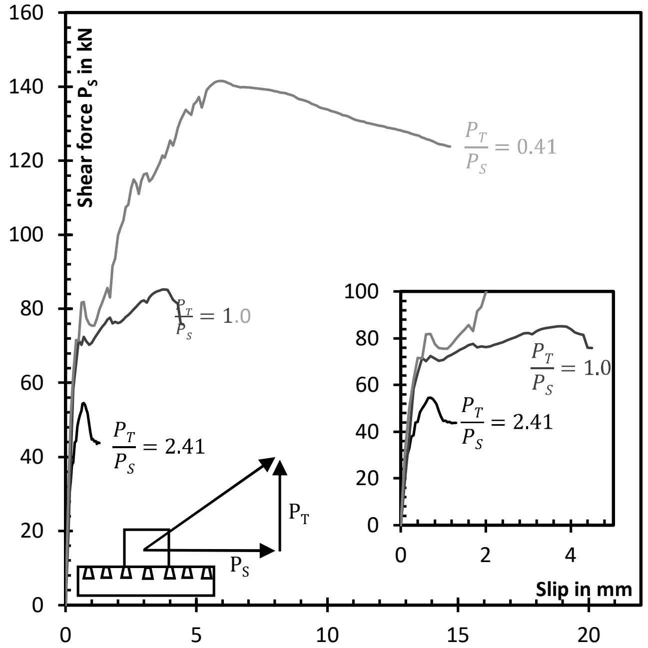

Figure 8 Shear deflection behaviour of the slabs with a re-entrant steel sheet.

The characteristic shear capacity of the headed studs is 67.1 kN for a load ratio of 0.41. With increasing tensile load, the shear capacity of the headed studs decreases from 40.8 kN for equal tension and shear load to 25.8 kN for predominant tensile load. The slip between the steel profile and the concrete decreases from 8.58 mm to 0.77 mm. For the case P_T/P_S=1.0, the characteristic slip is about 1.03 mm

Table 3 Test evaluation of the re-entrant profiles per headed stud

P_T/P_S	P_e [kN]	Cov [-]	P_{Rk} [kN]	δ_{ek} [mm]	δ_{uk} [mm]
0.41	70.8	0.03	67.1	0.34	8.58
1	42.8	0.02	40.8	0.47	1.03
2.41	27.3	0.03	25.8	0.34	0.77

For the composite slabs with a trapezoidal sheet in Figure 9, headed studs with a diameter of 19 mm were used in contrast to the other specimens. This makes it difficult to compare the dowel load-bearing capacity with the other specimens. However, comparisons can be drawn with the rest of the specimens on the deformation behaviour of the specimens.

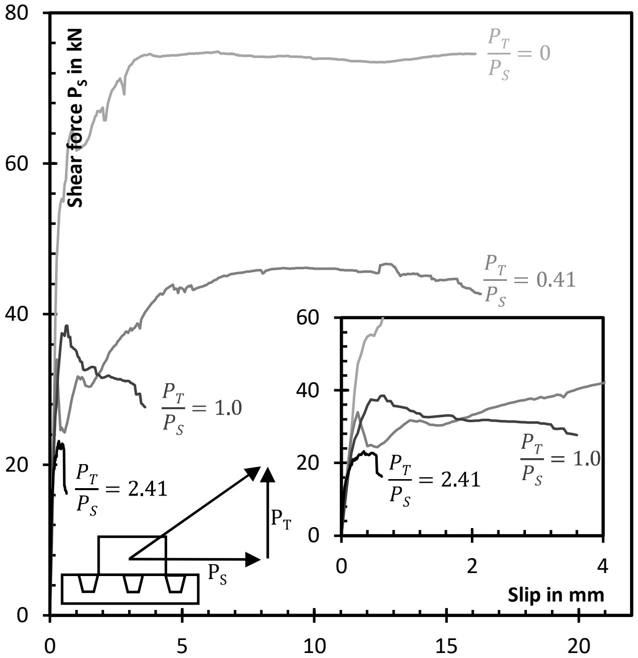

Figure 9 Shear deflection behaviour of the slabs with a trapezoidal steel sheet.

For pure shear stress, the characteristic slip between the steel profile and the concrete belt is 25.51 mm. Here, too, the slip decreases with increasing tensile stress. For a tension to shear ratio of 1.0, the characteristic slip value is 0.56 mm. The characteristic stud load-bearing capacity is 71.5 kN in pure shear and decreases here to 18.0 kN to a tension-to-shear ratio of 2.41.

Table 4 Test evaluation of trapezoidal sheet slabs per headed stud

P_T/P_S	P_e [kN]	Cov [-]	P_{Rk} [kN]	δ_{ek} [mm]	δ_{uk} [mm]
0	38.8	0.03	35.8	0.42	25.51
0,41	23.6	0.04	21.9	0.28	11.84
1	19.8	0.05	17.9	0.27	0.56
2,41	12.1	0.15	9.0	0.07	0.39

Figure 10 shows the load-deformation behaviour of composite slabs with a metal sheet with a modern geometry and an additional stiffener at the top chord. As for the other specimens, each graph shows the mean value of the measured slip values as a function of the shear stress P_S. Only with the load configuration of P_T/P_S= 0.41 does a peculiarity occur. Here, the graph of only one test is shown since the other tests were terminated prematurely due to a load drop of more than 40%. A slight drop in load can also be seen in the slip values for the specimen given in Figure 10, but the load of this specimen showed no significant drop after peak load.

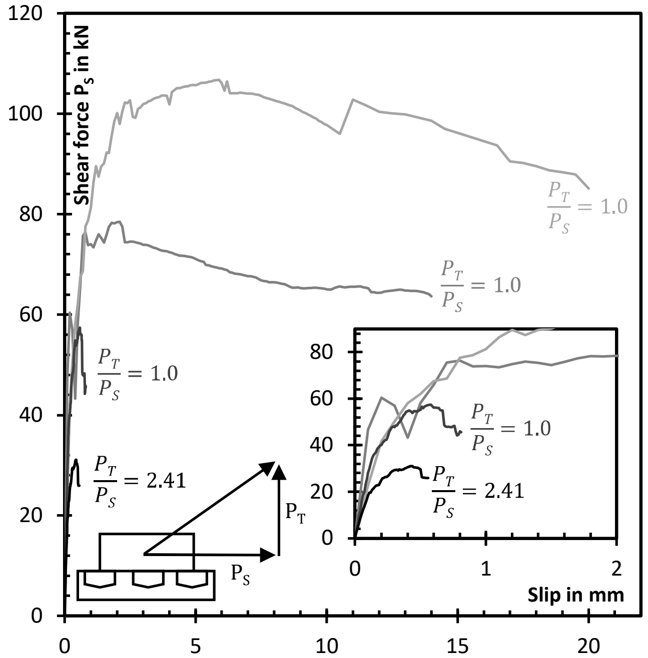

Figure 10 Shear deflection behaviour of the slabs with a modern steel sheet geometry with stiffener.

The characteristic load bearing capacity under pure shear loading is 89.4 kN with a characteristic slip of 8.5 mm. As in the case of the other specimen geometries, a decrease of the stud load-bearing capacity and a reduction of the slip with increasing tensile forces can be observed. At a ratio of P_T/P_S=1.0, the stud load-bearing capacity is still 53.0 kN and the characteristic slip is 0.56 mm. Up to a tension-to-shear ratio of 2.41, the shear load capacity decreases further to 28.7 kN. The characteristic slip value is still about 0.28 mm.

Table 5 Test evaluation of steel sheet slabs per headed stud

P_T/P_S	P_e [kN]	Cov [-]	P_{Rk} [kN]	δ_{ek} [mm]	δ_{uk} [mm]
0	54.5	0.10	44.7	0.74	8.50
0,41	39.3	/	/	/	/
1	29.3	0.05	26.5	0.23	0.56
2,41	15.9	0.05	14.4	0.18	0.28

The ductility of the shear connectors is evaluated under combined loading. The shear connectors show ductile load-bearing behaviour under pure or predominant shear loading. If the tension-to-shear ratio increases, ductile load-bearing behaviour can no longer be assumed.

3 Conclusions

The paper presents the investigation on the load-carrying behaviour of composite beams with large web openings. 60 pull-outs tests are performed to investigate the load-slip behaviour of headed studs under combined tensile and shear loading for different slab geometries. Due to the local disturbance in the steel beam, the headed studs at one edge of the web opening are affected by this load combination. The tests were carried out on both solid and composite slabs under 5 different tension-shear ratios.

Due to the reduced shear capacity of the steel girder in the web opening area, the shear connectors transfer high tensile loads to activate the shear capacity of the concrete slab above the opening. The results of numerical simulations show that the magnitude of the tensile stress of the shear studs at the edge with higher global bending moment of the opening can exceed the shear stress, resulting in ratios of tension-to-shear stress $P_T/P_S \geq 2.41$. A comparison of these findings with the results of the pull-out tests, it is obvious that significant changes in the ductility capacities of the headed studs occur. Therefore, it may not be able to define all headed studs in the region of the web opening as shear connectors of the same ductility category according to prEN 1994-1-1 [4]. prEN 1994-1-1 [4]. also covers the design of composite beams with web openings but does not provide any information on the shear connectors or the degree of shear connection for this specific design situation [6].

Test results show for increasing tension-to-shear load ratios a significant drop of shear capacity and slip capacity as well. This load-slip behaviour must be considered in the global design of the composite beam as well as in the local design of transfer of vertical shear forces between steel beam and slab at the edge of the opening. Test results will be used to improve existing finite element models for further numerical investigations.

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