Small scaled shear connectors in HSC/UHPC

Martin Classen, Martin Herbrand, Alexander Stark, Josef Hegger

Institute of Structural Concrete, RWTH Aachen University, Germany

Abstract: Through the use of ultra-high-performance concrete (UHPC) in composite construction, slender, wide spanning and highly sustainable composite elements can be realized. Due to its favorable ratio of strength to weight, high-strength concrete allows for a significant reduction in cross-sectional dimensions compared to normal-strength materials. For certain applications, the thicknesses of concrete slabs can thus be reduced to less than 30 mm. However, for such slender HSC/UHPC slabs the applicability of conventional shear connectors, such as headed studs, is no longer possible. The systematic connection of the cross sections requires novel, small scaled connectors transmitting shear forces in the composite connection. A novel welding method allows for the production of pin structures, which can be used as innovative small scaled shear connectors in HSC and UHPC. In this paper the local and global load carrying and deformation behavior of small-scale shear connectors is analyzed by experimental investigations.

Keywords: High performance materials (UHPC, stainless steel), slender composite structures, pin-connectors,

1. Introduction

Steel-concrete composites combine the favorable material properties of structural steel and concrete in an optimal way. The concrete is arranged in the compression chord and the steel is arranged in the tensile zone. To reach the whole composite strength among the two composite materials it is necessary to have effective connectors. In addition to their high load capacity and stiffness, the connectors need to have a sufficient deformation capacity. Compared to conventional steel-concrete composites, the load capacity of the composite structures can be significantly increased by using high-strength materials (e.g. high-strength steel and high-strength concrete) (Heinemeyer, 2012).

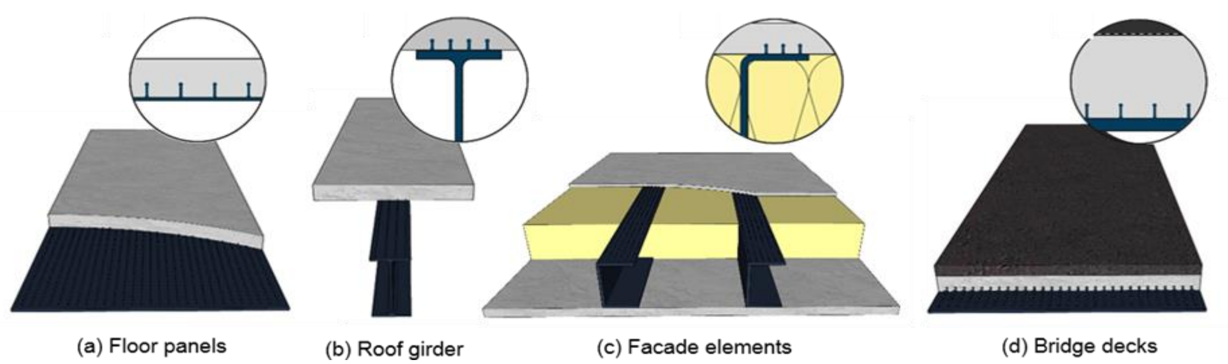

Figure 1. Applications for small-scale shear connectors.

This paper is about filigree composite structures, which consist of thin steel sheets combined with layers of high-strength and ultra-high-performance concrete (UHPC). The composite mechanisms between steel and concrete are ensured by small-scale shear connectors, shaped like a pin, which are produced directly from the welding wire using a novel welding process.

Potential applications for these filigree composite surface structures are in the range of floor panels (a), roof girders (b), façade constructions with thin-walled concrete sandwich elements(c) and in composite bridge decks(d) (Figure 1) (Claßen, 2015).

2. Production and materials

2.1. Welding process

The pin-connectors are produced directly from the welding wire using a novel pulsed welding process with dynamic wire pull back (Schierl, 2005), which is depicted in figure 2. At the present time, pins can be produced up to a height of about 5 mm depending on the wire diameter. In the current research project (Reisgen, 2012), the possibilities and limits of the pin-welding process are analyzed in terms of geometry, material and heat-affection. It is the aim to best suit the geometrical and material-related properties of the pins on the requirements of steel-concrete composites.

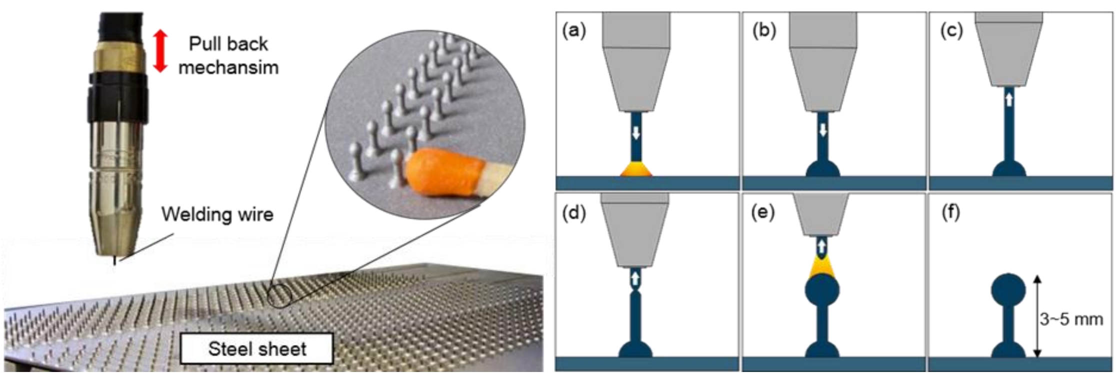

Figure 2. Schematic diagram of the CMT welding with illustration of the dropping process (Bruckner, 2005).

2.2. Metallurgical parameters of the pins and sheets

For the production of thin-walled composite structures sheets of austenitic steel (1.4301) are used. The use of these stainless steels is due to a large application potential of pin structures in façade construction. In future, the application of common structural steel is also planned. In the welding process, appropriate welding wires out of stainless steel 1.4316 with a nominal tensile strength of 590 MPa are used. In Figure 3 (a) the hardness of a pin is shown over its height. The hardness was evaluated using the method proposed by Vickers (DIN EN ISO 6507-1). It indicates, that there are only small hardness peaks in the area of the pin shaft and the pin base, which do not affect the structural behavior of the pin in composite constructions.

2.3. High-strength concrete (HSC) and ultra-high-performance concrete (UHPC)

In order to achieve a completely embedding of small-scale shear connectors in the concrete matrix, a small maximum grain diameter and high fluidity of the concrete are desirable from the perspective of concrete technology. These requirements also arise in the production of textile-reinforced concrete. Therefore, a fine-grained concrete mixture which was developed for textile-reinforced concrete applications (Hegger, 2012) is used in the production of thin-walled composite structures. Due to its high cement content and the small fraction of coarse aggregates, the fine concrete has a smaller elastic modulus and greater ductility than normal concretes of the same strength. The fracture energy of fine concrete is reduced due to the distinct homogeneous structure compared to conventional concrete, while the studies on creep characteristics and creep resistance of fine concrete gave similar results as for conventional concrete (Kulas,2015). The stress-strain curve of fine concrete can be described according to DIN 1045-1 taking into account the experimentally determined fracture strains. The developed concrete mix has a maximum grain diameter of 0.6 mm (0,02 in) and a compressive strength of about 70 MPa. Besides the use of high-strength fine concrete, the combination of the shear connectors with ultra-high-performance concrete (UHPC) is analyzed in the context of the current research project (Reisgen, 2012). UHPC is a dense structured concrete, which, due to the combination of optimized mixture designs with steel fibers, has an extremely high characteristic compressive strength (> 150 MPa), bending tensile strength (> 40 MPa) and elastic modulus (> 50 GPa), making it ideal for filigree and slender structures. Through the use of reactive (e.g. silica fume) and inert additives (e.g. quartz), the microstructure of the hardened cement paste is, in order to have a better processability associated with a very low water-cement ratio (generally ≤ 0.25), high in solids and of a low porosity. The addition of steel, glass, carbon or plastic fibers can influence ductility and strength affirmatively. A sufficient ductility and a crack bridging effect can only be guaranteed with high tensile strength and with high elongation at rupture of the fibers. The material behavior under compressive stress for conventional, high-strength and ultra-high-performance concrete is shown in Figure 3 (b) in form of stress-strain relations.

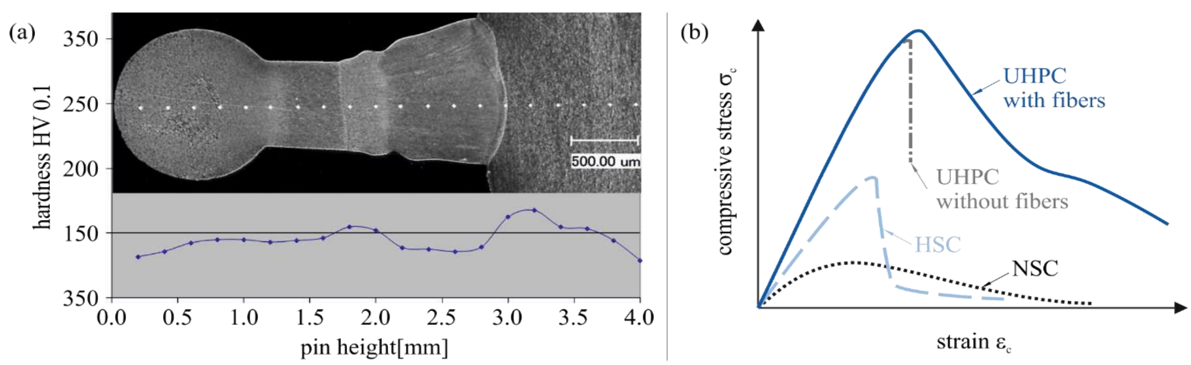

Figure 3. Hardness testing on a pin (a), stress-strain relationship of various normal and high strength concretes according to (Leutbecher, 2008) (b).

3. Experimental analysis

3.1. Shear tests

To analyze the pins under shear stress, push-out standard tests (POST) according to EC4 (Eurocode 4, 2012) are realized. For this purpose, a scaled test set-up with a bearing below the concrete slab and a load application on top of the steel sheet is used (Figure 4, left). The experimental procedure consists of 25 force-controlled load cycles to loosen the adhesive bond, a force-controlled start-up process to 60 % of the expected fracture load and a displacement controlled load of the test specimen until failure. For the evaluation of the experiment, the influence of the horizontal bearing of the concrete slabs is examined first. The measured force-slip curves are presented in Figure 4 (right). The experiments show a clear dependence of the fracture load to the horizontal bearing. If a gaping of the composite joint is prevented by a horizontal bracing of the concrete slabs but without initial clamping force (Figure 4, experimental setup with bearing), shearing occurs on the pin base (steel failure) at an ultimate load of approx. 600 N per shear connector. If the horizontal bracing of concrete slabs is omitted (Figure 4, experimental setup without bracket), the usual failure of the composite material is a concrete failure. The concrete wedge in front of the pin dowel is strongly compacted. This compaction process is accompanied by a large increase in pin deformation. Additionally, a pull-out of the pin and the surrounding concrete occurred after exceeding the shear capacity of the pin. This concrete failure already occurs on an average load level of 450 N. Thus, the fracture loads of experiments without horizontal bracing are on average 25 % below the fracture loads of experiments with horizontal bearing.

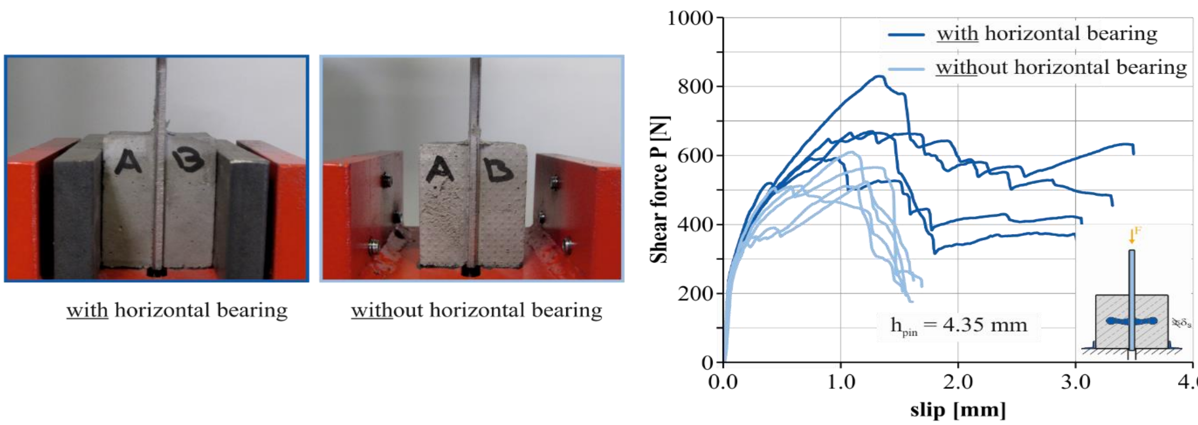

Figure 4. Shear tests: experimental setups (left), force-slip relationship (right).

3.2. Composite slab and beam tests on the global load-bearing characteristics

To research the global load-bearing characteristics of pin structures in composite construction, beam tests are performed under bending load. This is supposed to detect the required deformation capacity of the shear connectors and it shall verify the transferability of the local support mechanisms on the global load-bearing and deformation behavior. The test program is composed of bending tests on composite beams and composite panels.

3.2.1 Composite slab tests

First of all, composite slabs according to Table 1 were tested. The varied experimental parameters of these four-point bending tests on composite panels are the concrete strength f_{ck} and the number of pins in the composite connection. Here, the panels with full shear connection had a transverse pin spacing of 10 mm and a longitudinal spacing of 10 mm, while the longitudinal pin spacing of the panels with partial shear connection was increased to 20 mm.

Figure 5 (right) shows the test setup with the static system and a cross section of the test on the composite panels. In the tests the applied load and the vertical displacement were measured at mid span. In addition, the strain distribution on the steel and the concrete slab and the slip in the composite joint were measured. In Figure 5 (left), the moment-deflection curves of the bending tests on composite panels are shown. The influence of the higher E-modulus of UHPC compared to high-strength concrete is apparent. Assuming a full plastification of the composite cross sections, the slab with full shear connection made of UHPC reaches a plastic moment $M_{U,theo,UHPC}$ = 1,5 kNm and the beam made of HSC fails shortly before reaching a plastic moment of $M_{U,theo,HSC}$ = 1,3 kNm.

Table 1. Characteristics of slab tests.

		f_{ck} [MPa]	E_{cm} [MPa]	$R_{0,2\%}$ [MPa]	R_m [MPa]	Number of Pins	$M_{u,theo.}$* [lb-ft]	$M_{u,test}$ [lb-ft]
full shear connection	HSC	89	33.100	308	642	232	958,8	914,6
	UHPC	180	42.300				1.106,3	1.128,5
partial shear connection	HSC	89	33.100			120	885,1**	833,4
	UHPC	180	42.300				1.032,6**	899,8

* calculated with measured material and geometry values
** according to partial connection theory

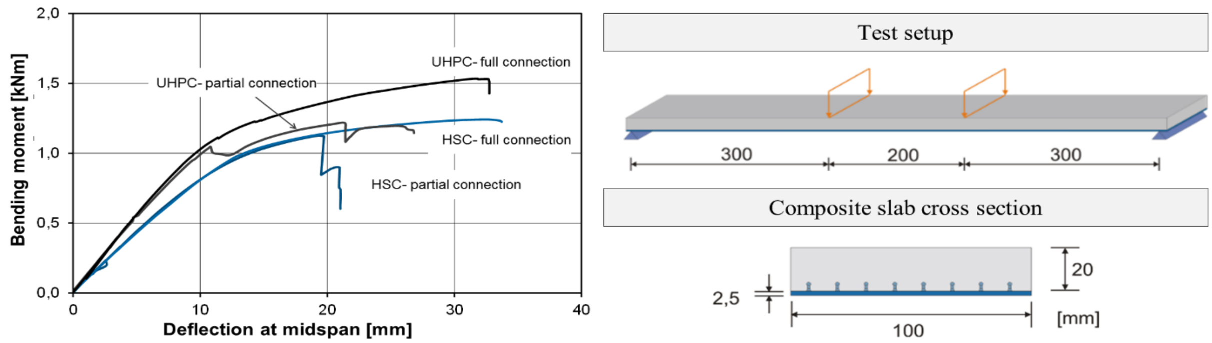

Figure 5. Experimental results of composite slabs (left), static system and cross section (right).

The failure modes of the composite panels made of HSC and UHPC are generally comparable. The panel with full shear connection collapses in the compressive zone of the concrete slab in the near the load application. In contrast to the previous failure mode, the panels with partial shear connection collapses in the composite joint. When a relative displacement of about 1 mm is reached, the pins shear off, beginning in the area of the load application. The fracture pattern shows disrupted concrete cones in the composite connection near the load application and sheared off pins (steel failure) near the bearings. In the region of the load application, a concrete failure of the pins with high compaction of the concrete wedge in front of the pin dowels occurred. After exceeding the shear capacity of the pins furthermore a concrete pry out cone developed. This concrete cone can be observed after the test indicating a concrete failure. To analyze the modes of failure and the deformation capacity of the pins in a composite structure, computed tomography (CT) 2D and 3D images of the deformed pins in the sample are generated. The results of a CT scan on a tested panel are shown in Figure 6. The 2D image (Figure 6, left) demonstrates the strong deformation ability of the pins on the pin base in UHPC. At the transition to the shaft an incipient crack in the steel is visible. Figure 6 (right) shows a disrupting concrete cone of a pin, oriented to the lower side of the HSC.

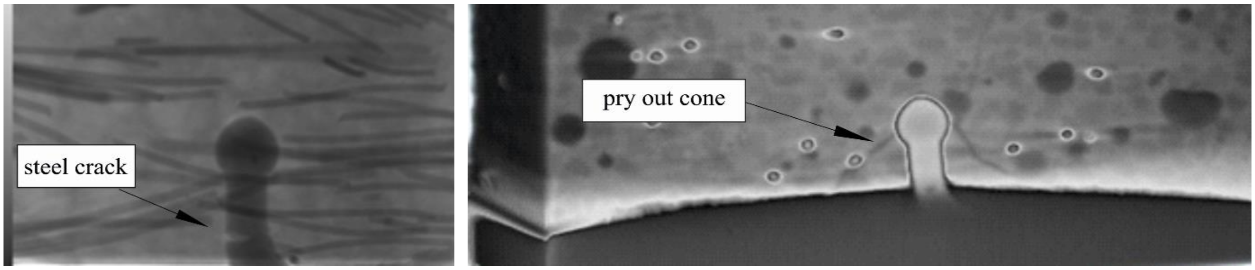

Figure 6. Results of CT scans in UHPC (left) and HSC (right).

3.2.2 Composite beam tests

Besides composite slab tests, this paper introduces four composite beam tests (T1 to T4) with small-scaled pins. All of the beams were fabricated identically in regards to the cross dimensions and the used materials and tested in a four point bending test. Here, the four specimens T1 to T4 only differ in their degree of partial shear connection and their spans. The investigated cross section had a height of 98,5 mm (3,88 in) and consisted of a 78,5 mm (3,09 in) high steel beam (welded I-profile, stainless steel 1.4301, $R_{p0,2\%}$=355 MPa, R_m=655 MPa) and a 20 mm (0,78 in) thick concrete chord (fine concrete with f_{cm} = 89 MPa, max. grain size < 0,6 mm (0,02 in)) (Figure 8). The pins were formed out of a 1,2 mm (0,04 in) thick welding wire (Steel type 1.4316, $R_{p0,2\%}$=350 MPa, R_m=570 MPa) with a height of 5,1 mm (0,2 in).

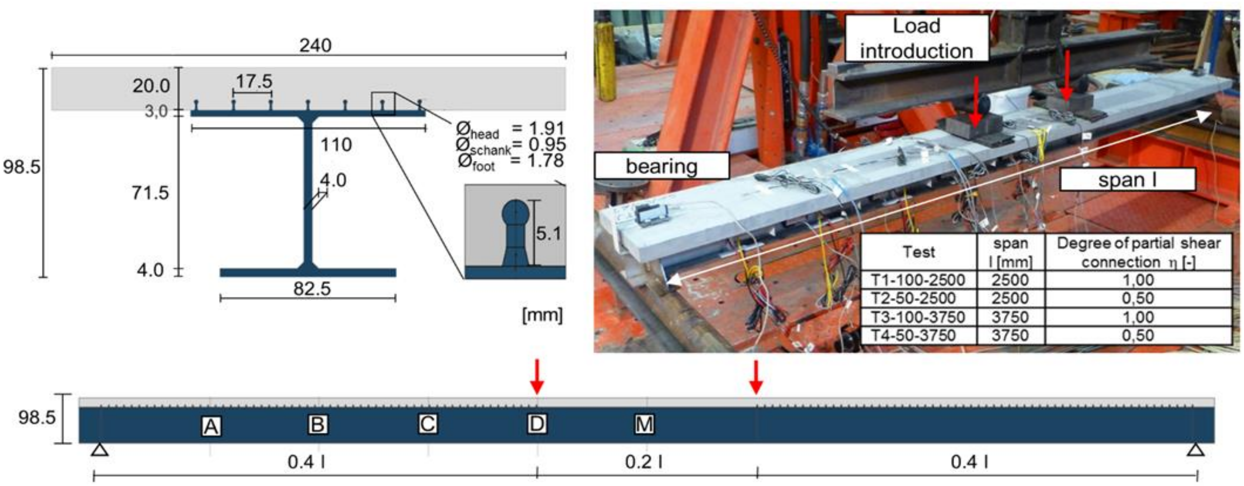

Figure 7. Dimensions of the cross section and test setup of the composite beam tests T1 – T4.

The pins were distributed equidistantly over the shear lengths. For the shorter beam (2,5 m (98,43 in)) a longitudinal spacing of 35 mm for partial shear connection and a spacing of 17.5 mm for full shear connection was chosen. For the 3,75 m (147,64 in) beam the spacing was 26.5 mm (full shear connection) and 52.5 mm (partial shear connection). In consequence, for both spans a theoretically full shear connection (η= 100 %) and a partial connection (η= 50 %) were available. In transverse direction there was a consistent distance of 17,5 mm (0,69 in). Figure 7 shows the dimension of the cross section, the test set-up and the test program. The deflections and slip were measured by displacement transducers; the load was applied by a servo-hydraulic cylinder with the deformation controlled. Figure 8 (top, left) shows the moment-deflection relation of the beam with full shear connection T3. The beam reached a failure moment of 15,2 kNm (11.210 lb-ft) with a maximum deflection of 165 mm (6,5 in) in the span middle. During the experiment there was an even strain distribution over the composite cross section with zero strain in the composite connection (Figure 8, bottom, left). The compression of the concrete chord on the upper side of the cross section ($\varepsilon_{c,100\%}$ = -3,3 ‰) reached the maximum acceptable concrete stress, at the maximum load level (Load step 100%). This resulted in a concrete compression zone collapse of the composite beam (Figure 9, left). The fully shear connected beam T1 showed a similar load-deformation behavior as T3 and confirms the prior described observations.

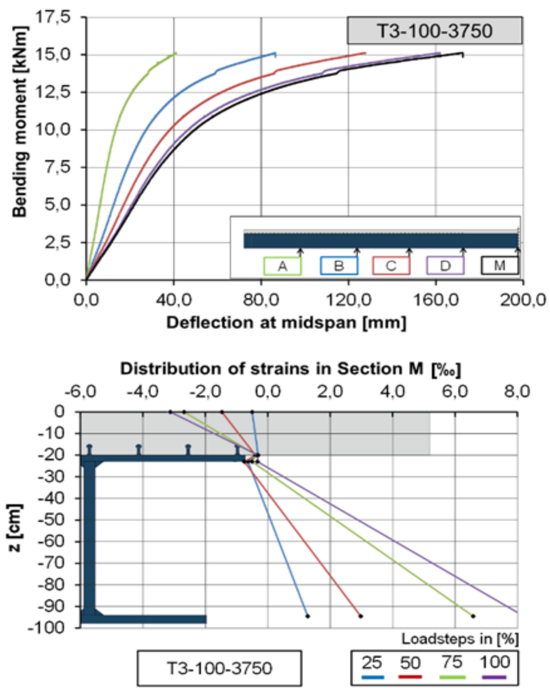

Figure 8. Bending moment-deflection curves at midspan (top) and strain distribution (bottom) of the beams T3 (left) and T4 (right).

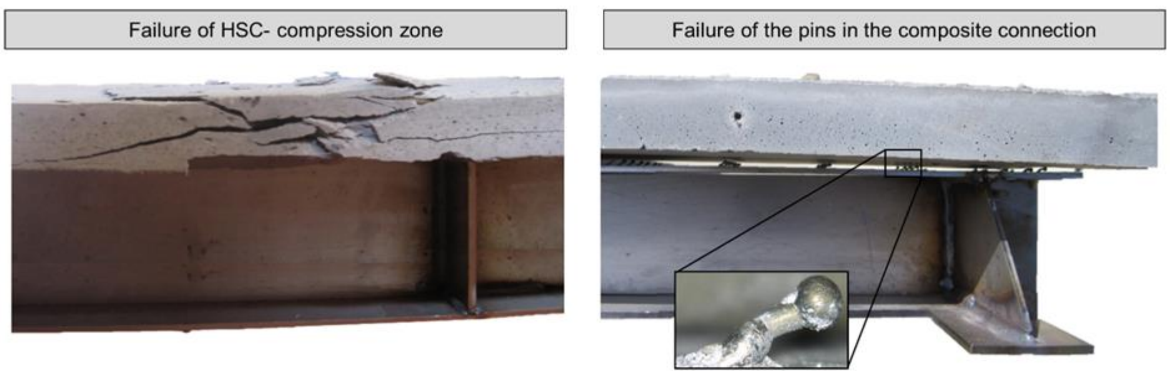

Figure 9. Failure of HSC- compression zone (left); Failure of the pins in the composite connection (right).

The load and deformation behavior of the beams with partial shear connection T2 and T4 differed from the beams with full shear connection. The in Figure 8 (right) illustrated strain distribution for partial connection had two zero crossings and a significant delta strain in the composite connection (flexible bond). The global bending collapse of the composite beams with partial shear connection was caused by a local shear collapse of the pins in the composite connection (Figure 9, right). Here, the beam T2 reached a maximum moment of 15,0 kNm (11.063,4 lb-ft). Beam T4 failed at 11,5 kNm (8482 lb-ft).

4. Conclusion

The research on load-bearing mechanisms of novel, small-scale pin shear connectors between steel and concrete is a project funded by the German Research Foundation (DFG). This paper gives an overview of current and future experimental studies on the behavior of small-scale pin shear connectors in filigree composite structures. To research the local load-bearing behavior of the pins that are formed directly in the welding process, small-scale shear tests are performed. To research the global structural behavior in composite structures, tests on composite beams and composite panels with pin shear connectors are conducted. The load-bearing and deformation capacity of the beams show a clear dependence on the degree of partial shear connection. Based on these experimental results, engineering models will be developed in the future. At the time being, additional investigations concerning the required ductility of the shear connectors are in progress.

5. References

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