

# ON THE EVOLUTION OF STEEL-CONCRETE COMPOSITE CONSTRUCTION

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structural analysis and development of structural forms, use of construction for dating historical fabric

## Abstract

Little has been written so far about the historical development of the joining of rigid elements made from steel and concrete – steel-concrete composite construction. This article therefore describes the individual phases in such a way that the reader gains an overview of the evolution of composite construction with steel and concrete.

The composite beam in the sense of Emperger's ideal of the friction/adhesion bond between the materials marked the initial phase (1850–1900). This was followed by the constitution phase (1900–1925) with its constructional separation of the elements of the cross-section. During the establishment phase (1925–1950) it was gradually realized that the elements of the cross-section had to be connected structurally, initially as positional restraint, later as mechanical shear connector. The quantified connection of the elements of the cross-section through standardized testing and the formation of theories in the classical phase (1950–1975) enabled the realization of multiple forms of steel-concrete composite construction for industrial buildings and bridges.



Figure 1: Steel beams with welded bar connectors for the new Herdecke Bridge (1951) over the River Ruhr (source: German Federal Ministry of Transport & Digital Infrastructure)

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## INITIAL PHASE (1850–1900): THE COMPOSITE BEAM

The first structures with iron sections and concrete preceded the emergence of reinforced concrete with non-rigid round bars as propagated by Monier (Bracher 1949). As early as 1808, Ralph Dodd (1756–1822) was granted a patent for suspended floors: “malleable iron” tubes with “ears or flanges” were filled with “artificial stone” to form a composite beam. The floor patent of James Frost already includes “iron ribs” with the intermediate “compartments” filled with “cement”. The suspended floor of Nathaniel Beardmore (1816–1872), patented in 1848, uses riveted I-beams with concrete in the intermediate bays and permanent iron formwork. The “fireproof” floors of Henry Hawes Fox were successful; they were patented in 1844 and marketed by James Barrett, and employed cast iron, from about 1851 wrought iron, upturned T-beams or I-beams (Fig. 2). Fox shifted the iron beams to the tension zone of the floor (Hurst 2001), and sometimes placed them outside the concrete of the floor itself: “The force of compression acts upon the joists, only through the medium of the concrete.” Fox and Barrett were aware of the underlying stress flows in their floors. This aspect was perfected in 1873 by William E. Ward in the suspended floors of his “Ward Castle”, which are in the form of a T-beam with rigid tension flange, albeit still encased in concrete.

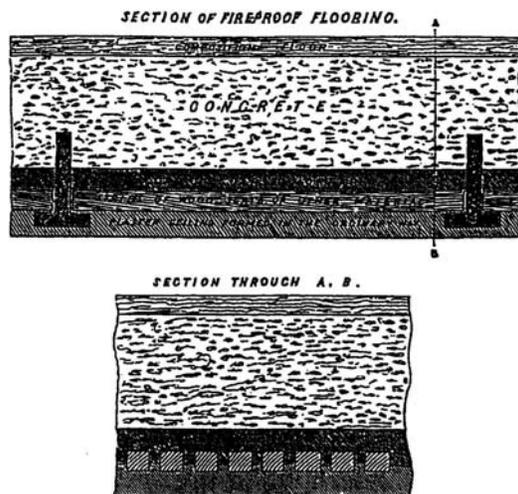


Figure 2: Suspended floor with cast iron joists by Fox & Barrett, pre-1851 (Hurst 2001)

A contemporary state of the art report by Paul Christophe (1902) shows a number of slab and beam-and-slab systems with steel sections available on the European market at that time. For example, the *Steinbalkenkonstruktion* of Fritz Pohlmann, formed by a T-beam over a perforated, asymmetric rolled section, the iron bulb beam, with flat iron hoops forming a shear-resistant connection to the concrete compression zone (Emperger 1904) (Fig. 3). Another example is Mathias Koenen’s (1849–1924) flat-soffit, later (from about 1892) ribbed, floor in which the underlying steel sections carry the tension and the arching concrete infill sections are solely responsible for carrying the compression. Despite the lack of shear connectors, tests confirmed Koenen’s assumptions regarding the structural behaviour (Christophe 1902).

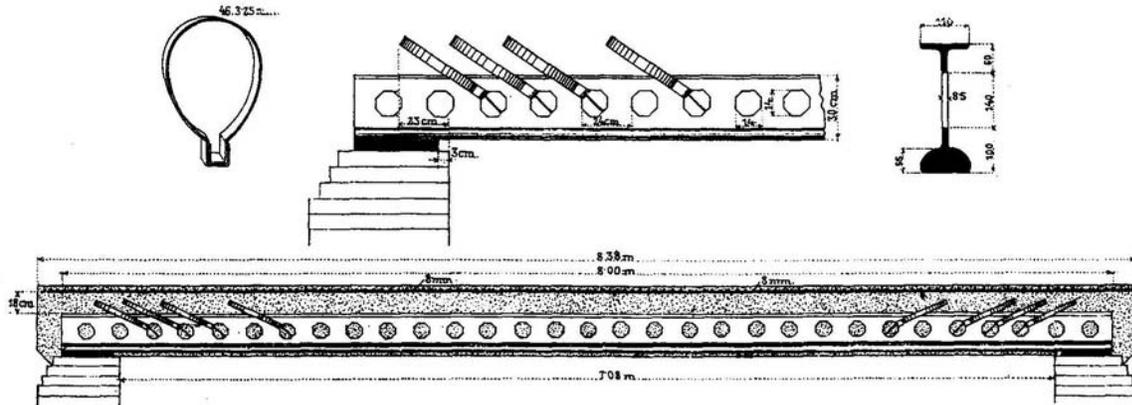


Figure 3: The Pohlmann floor, 1901 (Emperger 1904)

### CONSTITUTION PHASE (1900–1925): CONSTRUCTIONAL SEPARATION OF THE ELEMENTS OF THE CROSS-SECTION

As soon as reinforced concrete started to be used as an engineering material in structures (a date we shall take as 1886, when Mathias Koenen's design equation for reinforced concrete slabs was published), so it was regarded as a composite material. No distinction was made between non-rigid and rigid reinforcement; instead, the magnitude of the composite action was the important issue. Consequently, both types of reinforcement had to be fully encased in concrete.

Extensive tests between 1907 and 1909 by Carl von Bach (1846–1931) at the Materials-Testing Institute in Stuttgart (Emperger 1912) resulted in a much smaller “resistance to slip” for steel sections compared with non-rigid round bars. In addition, at the onset of movement, the steel sections burst open the concrete. In a brief submission, Koenen, too, drew attention to “the dangerous shearing-off behaviour” of steel sections encased in concrete. These concerns of von Bach and Koenen may suffice as the first indications of the mutual displacement of the different rigid elements. Both recognized that bond is a poor way of transferring load between rigid concrete and steel sections.

Notwithstanding, Emperger (1912) specified the same design rules for both types of reinforcement. However, he did mention that rigid reinforcement is less consistent with the nature of reinforced concrete and the strains in both materials influence each other – a fact that unfortunately had to be left out of the design proposal. Hager was more specific (1916); he explained that the interaction of large steel beam sections in slabs, encased in concrete, could only be clarified by carrying out tests. So the ultimate load model remained within the confines of classic steel construction, assigning the longitudinal load-carrying capacity solely to the steel sections, the transverse load-carrying capacity to the unreinforced concrete. The higher neutral axis of the cast-in steel beam section permitted the permissible stresses in the steel to be increased by 10%.

Around 1920 Rudolf Saliger (1873–1958) remarked that “particular measures presume the consistent action of concrete and rigid reinforcement”. (Saliger illustrated this with a flat steel bar riveted in place and bent up at 45°.) However, although this remark pointed the way forward, its significance was initially neglected (Saliger 1920).

Immediately after reinforced concrete started to be used as an engineering material, Joseph Melan (1853–1941) was the first to realize that concrete and encased steel trusses contributed

jointly to carrying the loads (Melan 1911) – initially for vaulted floors (1891), later in arch bridges in the mid-1890s in the USA. In his *Bogenbrücken in Eisenbeton*, Melan relieved the load on the concrete arch by using suspended centering such that between a third and half of the concreting load was carried permanently by rigid reinforcement.

At about the same time, cast-in rolled beams started to replace pure steel bridges for beam bridges with short spans because this form of construction was more economic (Wolff 1907). Whereas Wolff (1907) wanted to see this form of construction optimised by using suspended centering, Kommerell (1911) no longer considered the composite action for his standard bridges introduced by ministerial decree of the Royal Prussian Railways and assigned the reinforced concrete solely a transverse distribution action. The load-carrying reserves were taken into account through a moderate increase in the permissible steel stresses. Kommerell does not explain the function of the transverse connections (round steel bars) shown in Fig. 4. Following tests some 25 years later, Combournac (1932) assigned the transverse bars “passing through the webs of the steel sections” the function of a shear connector.

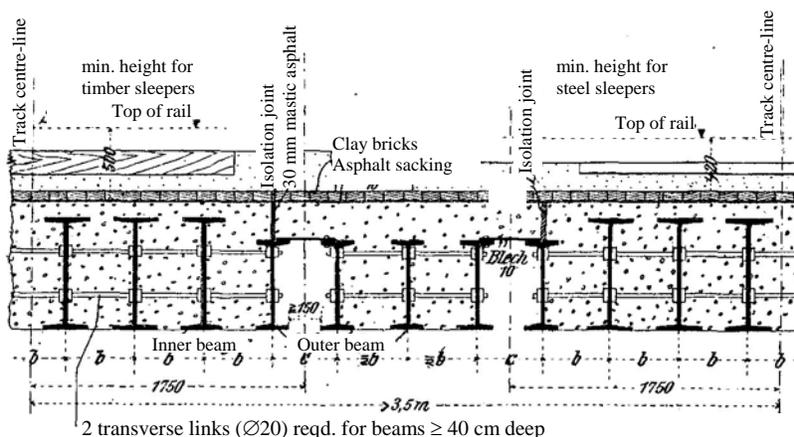


Figure 4: Typical section through railway bridge with rolled beams encased in concrete (Kommerell 1911)

The Aqueduc de l’Eau Froide near Villneuve, Switzerland, built in 1901, still has the classic, concrete-encased main beam. Short steel angles – more positional restraints than shear connectors – are riveted to the steel beams. Following the traditions of Grubenmann timber bridges, they reveal that the Swiss engineer realized the importance of using separate connectors to join rigid components instead of relying on friction.

Acheregg Bridge (1914) on Lake Lucerne in Switzerland was one of the first beam bridges in Europe to have a reinforced concrete deck that helps to carry the load through a friction bond (Rohn 1915). Its modern-looking beam-and-slab cross-section is made up of an approx. 23 cm deep reinforced concrete deck on top of two heavy, 800 mm deep rolled steel beams at a spacing of 3250 mm (Fig. 5). Lightweight steel cross-trusses link the rolled Differdinger “Greyträger 100 B” sections every 1.10 m. Both top flanges and about 20 cm of each web are cast into the underside of the reinforced concrete deck.

## ESTABLISHMENT PHASE (1925–1950): STRUCTURAL CONNECTION BETWEEN THE ELEMENTS OF THE CROSS-SECTION – FROM POSITIONAL RESTRAINT TO SHEAR CONNECTOR

Reinforced concrete slabs not cast monolithically with their supports require positional restraint; emergence of first constructional shear connectors.

### Developments in Europe

In Europe the interaction of the two materials of the composite initially continued to focus on the friction/adhesion bond between them. The first significant measurements of this were carried out between 1924 and 1926 by the Swiss engineer Adolph Bühler (1882–1951) under the auspices of Swiss Federal Railways (Emperger 1931). This was followed up by studies by the French railway engineer L. Cambournac (1932) and finally R. C. Kolm in Sweden (1936).

The early advice of the Austrian engineer Rudolf Saliger (Saliger 1920) for a mechanical bond between beam section and reinforced concrete slab in the suspended floors of buildings went unnoticed in Germany for about 15 years. Column/T-beam systems with concrete transferring the bond, activated via a Melan prestress, were lauded as state of the art for industrial buildings up until the early 1930s.

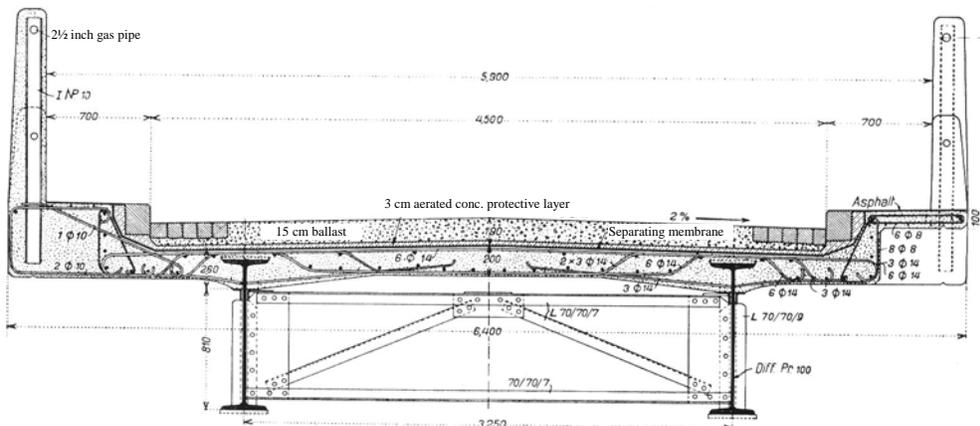


Figure 5: Section through Acheregg Bridge on Lake Lucerne, 1914 (Rohn 1915)

At the same time, Otto Schaub, senior engineer of the Swiss town of Biel, devised the “Alpha” steel-concrete composite form of construction (Voellmy 1934) – a fully developed composite solution with exposed beam sections connected to the overlying reinforced concrete slab via shear-resistant wave-shaped or curved round steel reinforcing bars. Tests by Mirko Roš (1879–1962) confirmed the effectiveness of these shear connectors. Prior to 1934 Schaub had already strengthened road bridges with welded helices. The small road bridge over the River Birs at Laufen and the Jäger Bridge over the Biel–Sonceboz railway line have been documented (Voellmy 1934).

Kurt Zendler, a former employee of IG Farben Ludwigshafen (now BASF), writing after the Second World War (Zendler 1950), reported that the first steel-concrete composite slabs had used connectors in the form of welded helices of round steel bars for a heavy industrial floor in Germany as early as 1934. Zendler’s work was supported and supplemented by the testing work of Hermann Maier-Leibnitz (1885–1962) in Stuttgart. By including dynamic loads and floor openings, those tests with round reinforcing bars, bent up at 45° in the longitudinal direction and

welded on, focused on the further development of steel-concrete composite construction for industrial structures. It is essential to mention here that the restrictions placed on the liberal Maier-Leibnitz by the National Socialist regime, and the poor light in which they portrayed him, hampered the development of steel-concrete composite suspended floors for industry over the long term. For decades, the omission of the use of the non-*n* design method and ultimate load analysis theory proved a drawback for German steel-concrete composite construction.

### A different course in Germany

Contrasting with this, the lightweight construction demanded by the Nazi regime, which also extended to steel-concrete composite construction, remained a German peculiarity until the end of the Second World War. In conformity with the ideology, the contributions stick to reducing the weight of steel by using the friction/adhesion bond of overlying, thin reinforced concrete slabs with orthogonal reinforcement and references to lightweight steel bridge decks built in the USA (Schaechterle 1934). At best, the shear-resistant connection between arched steel plates and concrete topping in the form of welded round steel bar anchors can be considered to be a contribution to the development of steel-concrete composite construction. Not until a new generation of engineers came along would German composite construction gain new momentum.

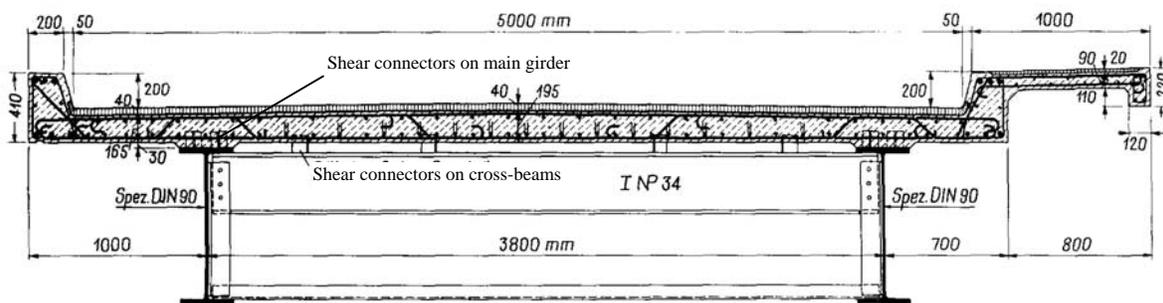


Figure 6: Section through Willerzell Viaduct at Lake Sihl, 1936 (Etzelwerk AG 1934/1935)

### Developments in Switzerland

In order to explain the composite action, the Technical Commission of the Swiss Bridges & Railway Structures Fabricators Association (T.K.V.B.H.) decided to carry out tests with cast-in rolled sections around 1929 (Stüssi 1932). This was the first report on the elastic-plastic behaviour of the composite cross-section and the lack of an effective friction/adhesion bond at the ultimate load case. To exploit the material of the connectors to the full, Stüssi recommended a “constructional slip restraint”, the effectiveness of which he ensured by carrying out an ancillary test with steel flats welded to the top flange. In 1934 Mirko Roš broadened contemporary knowledge by conducting tests with a welded round bar helix; one year later he supplemented this with dynamic tests, probably needed for Pont Bressonnaz (Albrecht 1945). Between 1942 and 1943 Roš (T.K.V.B.H. 1944) – inspired by Alfred Albrecht (1896–1955) – rounded off Swiss experience of shear-flexible and rigid-in-shear bond for static and dynamic loads (Albrecht 1945). The T.K.V.B.H. conference of 1944 reported on the leading position of Swiss engineers in Europe when it came to steel-concrete composite construction (T.K.V.B.H. 1944). The Stahlbau Zschokke AG company, managed by Fritz Bühler (1891–1959), turned the theory into reality in Europe: Willerzeller Viaduct over Lake Sihl in Switzerland (1936) was the first European bridge to have welded shear connectors in the form of channel sections (Fig. 6).

## Developments in the USA

The automobile and machinery industries in the USA were already demanding highly efficient, slim suspended floor systems in the years following the First World War. Julius Kahn applied for a patent for a composite beam in 1921, which was granted in 1926 (Kahn 1926). Alternating, bent-up flange cut-outs join the beam section to the reinforced concrete slab to form a modern-looking steel-concrete composite cross-section (Fig. 7).

Contrasting with that, R. A. Caughey's state of the art report (1929) on university tests between 1922 and 1929 takes us back to the friction/adhesion bond. Summing up, Caughey recommends a "mechanical bond" for the horizontal shear restraint without providing an actual practical solution.

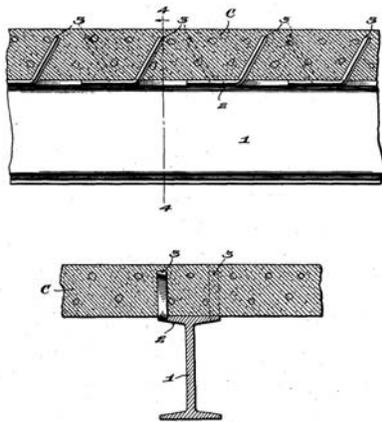


Figure 7: Composite beam (Kahn 1926)

Those tests were followed by the large-scale experiments on composite bridge beams carried out by Searcy B. Slack from 1930 to 1932 (Slack 1948). Slack refrained from using the pure friction bond and ensured the shear restraint by welding on connectors in the form of hooked reinforcing bars. Directly afterwards, in 1933, the Oregon State Highway Department erected a road bridge with a span of approx. 21.7 m whose five steel main beams were interconnected via reinforced concrete cross-beams to form a grillage. Riveted Z-shaped brackets ensure the mechanical bond for the overlying reinforced concrete slab. The shear pockets let into the reinforced concrete beams remain a nice feature (Paxson 1934).

## CLASSICAL PHASE (1950–1975): QUANTIFIED CONNECTION OF THE ELEMENTS OF THE CROSS-SECTION AND THE EMERGENCE OF STEEL-CONCRETE COMPOSITE CONSTRUCTION

Shortly after that, the first successful steel-concrete composite bridge in the USA for spans between 6 and 24 m appeared in the form of the "slab and stringer bridge". In these straight or skew beam-and-slab bridges with closely spaced steel beams, the reinforced concrete slab is solely responsible for ensuring adequate transverse distribution of the loads and resisting the punching loads of the wheels of heavy vehicles (Richart 1948). It was in 1938 that Newmark began to give this bridge type a theoretical basis, which led to the publication of his first design concept in 1943 (Newmark & Siess 1943). Backed up by extensive tests, Newmark (1948), together with Richart (1948) and Siess (1948), was able to finish his practical design concept shortly after the Second World War. The publication of the first design provisions by the

American Association of State Highway Officials (AASHO) in 1944 standardized the steel-concrete composite bridge in the USA for the first time.

The German Committee for Structural Concrete (DASt) was reconstituted on 27 April 1948. The knowledge that the many steel bridges destroyed in the war could be rebuilt more economically and lighter prompted the DASt to set up its “Composite Beam” subcommittee under the chairmanship of Wilhelm Klingenberg (1899–1981), who had already had his first taste of composite construction as long ago as 1929 under Hugo Junkers. He started his work in May 1949 (Klingenberg 1949) and straightaway established the international status of composite construction with the help of two conferences in December 1949 and April 1950 (Schleicher & Mehmel 1950). Klingenberg organized comprehensive series of tests to provide solutions for the remaining aspects. He was able to present most of the findings just two years later (Klingenberg 1952). The subcommittee submitted the first draft of a code of practice for the “design of composite beams for road bridges” as early as 1950. The introduction of DIN 1078 (steel-concrete composite bridge beams) in 1955 and DIN 4239 (composite beams in buildings) in 1956 brought Klingenberg’s code drafting work to a close for the time being.

In order to be able to quantify the load-carrying components of the steel and the reinforced concrete and the shear force that connects them at their interface, it was necessary to transfer the knowledge about creep and shrinkage from prestressed concrete to the steel-concrete composite. In addition, the connectors had to be designed, the influence of non-static loads specified and plastic theory experiments expanded (Klingenberg 1952).

The fundamental work of Franz Dischinger, published between 1936 and 1939, already provided a solid framework for design taking into account creep and shrinkage. This enabled Dischinger (1949) to design composite beams with and without prestress.

Some 20 years later, Sattler in Germany stood for the theory of the steel-concrete composite beam (Sattler 1953). The much more practical and more comprehensive calculation proposals of the idealized elastic modulus of Bernhard Fritz (Schleicher & Mehmel 1950), which he summarized in a book “for bridge-building practice” in 1961 (Fritz 1961), were happily and frequently used. However, Fritz was not acknowledged to the same extent by his peers.

The range of construction options for shear connectors at the steel/concrete interface was broad in the 1950s, and not standardized. A long discussion about rigid-in-shear and shear-flexible bond, involving a large number of connectors, led to the appearance of shear stud welding in the building industry from about 1960 onwards for attaching standard shear studs.

The built environment precedes scientific knowledge. Indeed, it often awakens the curiosity of researchers in the construction industry. Hellmut Homberg (1909–1990) (Schleicher & Mehmel 1950) provided German steel-concrete composite bridge-building with two early structures in the form of a bridge over the River Agger at Ehreshoven (built in 1946/1947) and another over the River Erft at Bad Münstereifel (built in 1948/1949). Klingenberg (1949) can list five early structures, of which the Lower Main Bridge in Frankfurt, prestressed via erection measures for dead and imposed loads, built in 1949, should be highlighted. Herdecke Bridge over the River Ruhr (Fig. 1) by Homberg and Dietrich Fuchs (Homberg 1951), opened for traffic in March 1951, contributed much to prestressed composite bridge-building. By 1957 there were some 60 large steel-concrete composite bridges on trunk roads in Germany. By the end of the 1950s, steel-concrete composite bridges could no longer compete with prestressed concrete and from then on were reserved for very slender, long-span beam bridges.

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