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EVOLUTION OF BRIDGES WITH STEEL-CONCRETE COMPOSITE SUPERSTRUCTURE. WHAT COMES NEXT?

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Abstract

Bridges have evolved over time from the simplest forms made from materials found in nature – wood and stone - to the complex shapes of today, made of concrete, steel, steel-concrete, and composite materials. If in the past the large dimensions of an obstacle impeded building a bridge, today this problem can be solved by choosing suitable materials, an advantageous structural system, and an erection method that favors the chosen solutions. The composite superstructures made of steel-concrete have started to be used more often in the construction of bridges due to their advantages. The scope of this paper is to analyze the evolution of road bridges with steel-concrete composite superstructure. There can be distinguished mainly 4 stages in the evolution of these types of structures. In the first two stages during 1850-1925 the connection between concrete and steel was achieved by the adhesion between the contact surfaces of the two materials. Starting with 1932 (stage III), a connection was realized that takes over the forces of friction that develop at the contact between the two materials. These connecting elements took different forms: loops the reinforcement, U, L, or ⊥ metal parts, shear stud connectors, and more recently composite dowels. The advantages of different types of connectors have been highlighted by various calculation methods, practical applications, and high productivity. Nowadays the construction of an impressive bridge has become a source of pride at an international level, a way to demonstrate the technological progress in the field. But what does the future hold in the field of composite structures made of steel-concrete?

Keywords: composite, superstructures, evolution, future

1 Introduction

The steel-concrete composite structures offer extremely efficient solutions for bridges. The advantages of these types of structures result through the judicious placement of the constituent materials of the element - steel, concrete, and reinforcement - aiming, as far as possible, the concrete to be placed in the compressed area, and the steel in the tensile area, [1].

2 Evolution of road bridges with steel-concrete composite structure

The history of steel-concrete composite structures is as old as the history of reinforced concrete. The evolution of steel-concrete structures can be divided into 4 stages.

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2.1 Stage I (1850-1900)

The first concepts of steel-concrete composite structures were used on the floors of residential buildings. From the 1800s, different variants of metal used in combination with concrete began to appear. In 1848 Nathaniel Beardmore (1816-1872) patented a floor that used riveted I-beams with lost metal formwork and concrete filling between the I-beams [Fig. 1a], [2].

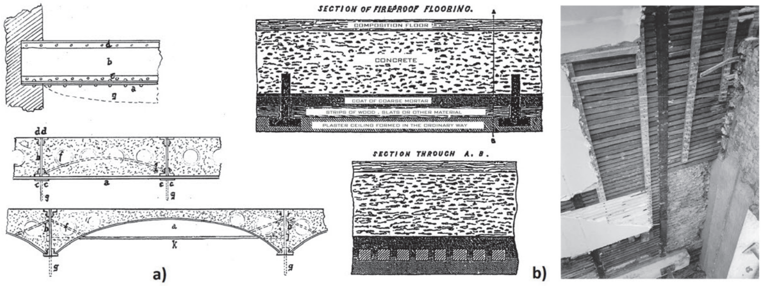

Figure 1 a) Suspended floor by Nathaniel Beardmore [2]; b) Suspended floor with cast-iron beams by Fox & Barrett [3]

On the fire-resistant floor patented by Henry Hawes Fox in 1844, cast iron was first used, but, from 1851 on, I or ⊥ steel beams became more common. The beams were partially positioned outside the concrete section, the compression force being taken over by the concrete section and the tensile force by the metal elements [Fig. 1b], [2].

In 1892 François Hennebique patented the use of flexible reinforcement for concrete elements and is considered the initiator of the use of reinforced concrete. However, it was necessary to use steel profiles to support the formwork or in the case of structures with larger spans. Although discussions were combining these two materials, only1902 that Fritz Pohlmann patented in Germany the steel-concrete composite structure, where the shear force between the two materials was taken over by the loops made of metal plate and the holes in the web of the metal beam [Fig. 2], [2].

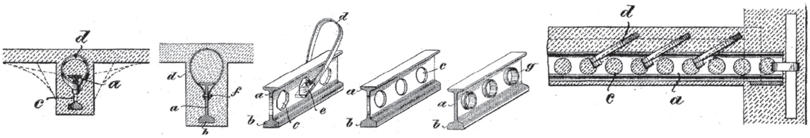

Figure 2 The Fritz Pohlmann floor [4]

2.2 Stage II (1900-1925)

As early as 1892, Mathias Koenen (1849–1924), made a structure where the tensile efforts were taken over by the flexible reinforcement and the compression efforts by the concrete section [Fig. 3]. He also used steel profiles embedded in concrete to make floors with large spans. Concrete has begun to be regarded as a composite material but no difference has yet been made between flexible reinforcement and rigid reinforcement (metal profiles) [2].

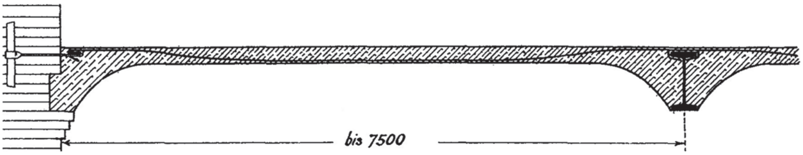

Figure 3 Section of Mathias Koenen's floor [2]

The tests carried out between 1907 and 1909 in Stuttgart by Carl von Bach (1847–1931) showed that as the load increased, in the elements having steel profiles, the cracks were more pronounced than in the elements that had flexible round bars. Also the phenomenon of dislocation of the concrete surrounding the metal profile appeared. Mathias Koenen draws attention to this dangerous phenomenon. Carl von Bach and Mathias Koenen admit that the adhesion between the concrete and the metal profile is less efficient than in the case of flexible round bars. However, in the design prescriptions developed during that period, no different rules are specified for the two types of reinforcement [2].

As early as 1904 Rudolf Saliger (1873–1958), an initial teacher in Kassel, then in Vienna, recognizes that once the adhesion between the contact surfaces of the two materials - concrete and metal - is lost, the resistance is reduced substantially. He recommended in 1920, as a special measure, the realization of a connection between the concrete and the metal profile by installing connectors in the form of plates bent at 45°. But his recommendation is not taken into account [2].

After understanding the vaulted floors, Joseph Melan (1853–1941) proposed a system that used spatial metal structures embedded in concrete. The steel structure was dimensioned to take over part of the wet concrete loading during the execution phase, and after hardening, both materials contributed to the bearing of the load [Fig. 4]. Thus, starting with the mid-1880s, the Melan system began to be used on bridges, and in1924 in the USA already being built over 500 bridges using the Melan system [5].

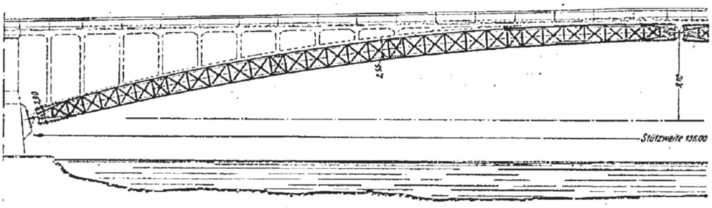

Figure 4 View of Elbbrücke Dresden – Melan System [5]

In 1902 José Eugenio Ribera patented a system similar to the system proposed by Melan, in which the entire weight of the concrete in the execution phase was taken over by the rigid reinforcement. After the hardening of the concrete, both materials contributed to the taking over of the loads [6].

For bridges with smaller spans, the solution of metal beams embedded in concrete was cheaper, especially for railway bridges. Otto Kommerell (1873–1967) proposed that this type of structure should no longer be considered composite and that the entire load would be taken over by the metal beams. The concrete should have the role of distributing the variable actions. He also proposed that where the height of the apron is greater, part of the web and the lower flange of the beams should not be concrete. In the drawings, he did not explain the role of the bars connecting the metal beams [Fig. 5] [8].

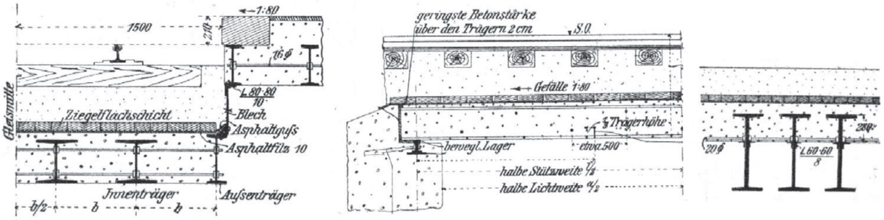

Figure 5 Typical detailing for railway bridge with rolled beams encased or partially encased in concrete [8]

Gradually the bridges made entirely of metal were replaced by those that included - in whole or in part - metal beams in concrete. In the first stage, the beams were fully embedded in the concrete, then only the upper flange and part of the web were integrated. The concrete slab was made of reinforced concrete and the bond with the steel beams was achieved by the adhesion between the contact surfaces of the two materials. One of the first bridges built in Europe (1914) with this solution is Achereggbrücke on Lake Lucerne [Fig. 6] [8].

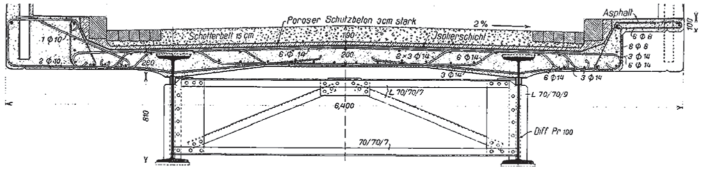

Figure 6 Section through Achereggbrücke on Lake Lucerne [8]

2.3 Stage III (1925-1950)

Even though in 1920, Rudolf Saliger recommended making a connection between the elements of the section by installing connectors, it was only in 1932 that connectors began to be assembled to achieve a connection between the two materials, going with the idea of a composite structure. At first, the connectors were arranged constructively in the form of round steel welded spirals. Gradually the connectors began to play a role of resistance, taking over the forces of friction that develop at the contact between the two materials [Fig. 7], [11].

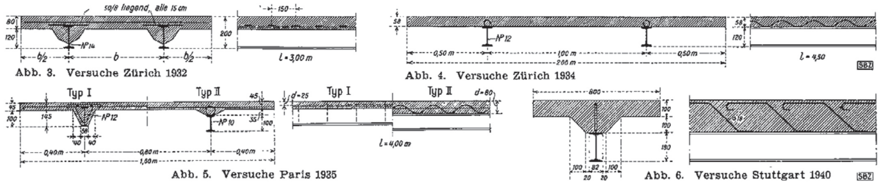

Figure 7 Various connection types [11]

Starting with 1932 the Verbandes der Schweizerischen Brücken- und Eisenhochbau-Fabriken (T.K.V.S.B.) decided to carry out experiments that first documented the elastoplastic behavior of the composite section. Several types of connectors were tested, but in principle, they were made of round bars bent at 45°, welded, and positioned in the longitudinal direction of the steel beams. Static and dynamic tests were carried out complementing the knowledge of the time [12, 14]. The Swiss become European leaders in the construction of composite structures. The Steinbach and Willerzell bridges over Lake Sihlee are the first European bridges that use specially dimension connectors to take over the shear between the two materials in the form of ⊥ welded to the upper flange [Fig. 8] [15].

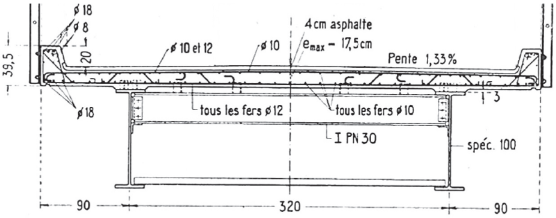

Figure 8 Section through Willerzell bridge on Lake Sihlee [15]

Typical for that period is the bridge over the Sava river in Zagreb. It has four spans and was built between 1938-1939. The connection between the main beam and the concrete slab was made by flexible connectors [Fig. 9] [16].

Figure 9 Bridge over the Sava river in Zagreb, Croatia [16]

In Spain, Puente de Tordera was completed in 1939. It was a bridge with a composite structure and had connectors in the form of round bars, [2].

In the U.S.A., bridges built in New York had to be light and resistant. That is why starting with Goethals Bridge (1928), George Washington Bridge (1931), and Tribourough Bridge (1936) the connection between the two materials (concrete and metal) has gradually improved, [2].

2.4 Stage IV (1950-today)

After the end of the Second World War, in Europe starts a program with the purpose of reconstructing the destroyed infrastructure during the war. That was the start of the development of composite structures. In 1950 the first set of rules for designing composite structures bridges was created and in 1956 DIN 1078 was adopted in Germany, [2].

Connectors made of round bars bent at 45° and welded on the upper flange of the beams were elastic. While those made of U, L, or ⊥ metal parts, completed by some loops in the reinforcement were rigid [Fig. 10a] [2].

Various discussions about connectors, in the end, led to the appearance of shear stud connectors in the 1960s. They were connected to the upper flange of the beams by welding. They proved to be very efficient because they had good behavior, high productivity, and they were easy to install due to the automation of the welding process [Fig. 10b] [2].

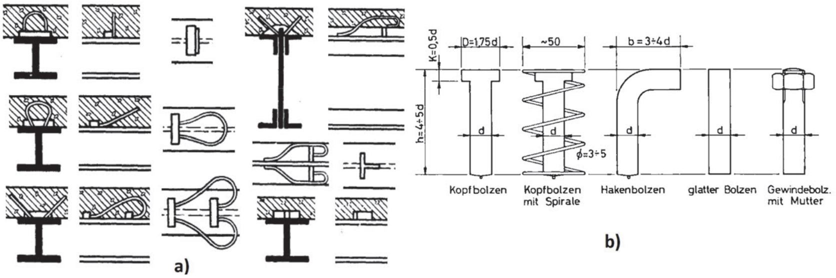

Figure 10 a) Typical shear connectors [2], b) Shear stud connectors [17]

Research has continued to focus on plastic analysis and how this type of structure influences the shrinkage and creep of concrete. The possibility of prestressing the concrete slab was also studied [2].

If until the 1950s composite structure bridges could not compete with those made of prestressed concrete, then this type of structure was used especially for bridges with large spans and thin decks [2].

Since that period, the evolution of steel-concrete composite structures has been closely related to the qualitative evolution of material characteristics, the improvement of design methods, and the development of manufacturing and execution technology. Figure 11 presents some typical composite bridge cross-sections which are used mainly nowadays.

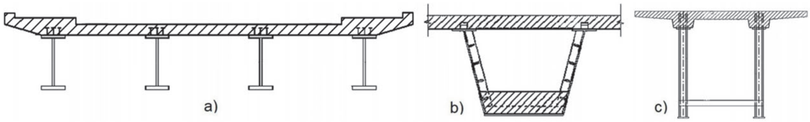

Figure 11 a) multi-girder section, b) double composite section for large span bridges above intermediate support, c) truss composite section [18]

Starting with 1998, prefabricated composite beams began to be used in the construction of bridges. This type of beams consists of a steel beam located at the bottom, thus taking over the tensile efforts, and at the top a formwork element made of reinforced concrete. The main advantage of these types of beams was the fact that they have a short time of assembly and fulfillment of quality standards due to their execution in superior conditions to those on-site [19].

The most expensive material in the composite section is steel, thus the engineers focused on optimizing the section based on internal stress distribution. Consequently, the upper flange was removed from the compressed area, the compression efforts being fully taken over by the reinforced concrete slab. The advantage of such a solution can be seen in Fig. 12 [8].

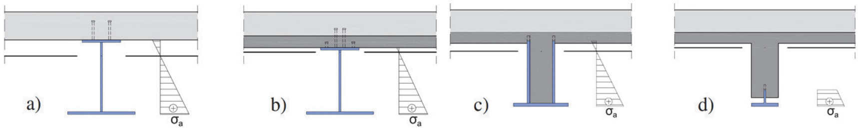

Figure 12 Stress distribution: a) conventional composite section, b) VFT® – construction method; c) VFT-WIB® – construction method; d) Section with external reinforcement (also VFT-WIB® section) [20]

By cutting the steel profile, an attempt was made to create a shape that would take the role of stud connectors - which were welded to the upper flange. The new shape of the steel profile is called composite connectors and they have had different shapes over time [Fig. 13]. This type of beam is called VFT® or VFT-WIB®. By cutting longitudinally an I type profile, according to a certain geometry, two identical T type profiles were obtained [20].
If the prefabricated beam has a length that cannot be transported, it can be formed of two sections that will be joined on-site and then mounted in the final position. The solution of joining the two sections is suggested in Fig.14 [21].

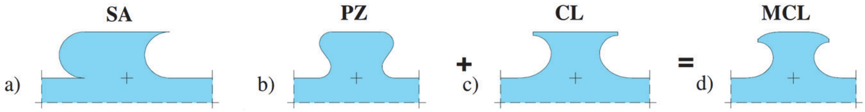

Figure 13 The shape of composite dowels: a) fin (SA), b) puzzle (PZ), c) clothoid (CL), d) modified clothoid (MCL) [20]

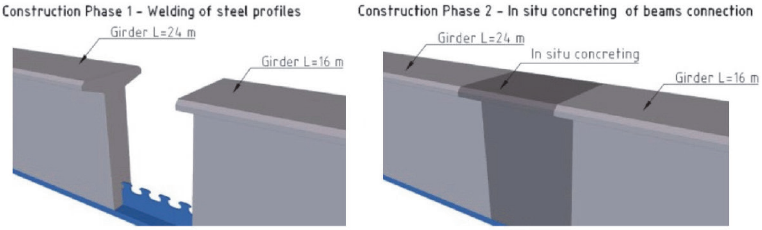

Figure 14 In situ connection of two sections of beams [21]

3 Conclusions

The use of steel and concrete in a unitary structural system took place long before the exact mechanical behavior of the composite elements was known. The connection was achieved by the adhesion between the contact surfaces of the two materials in the first two stages (1850-1925). Connecting the two materials has been discussed since 1932. There have been various variants of connectors studied over time. However, the development of calculation models and their validation in practice has revealed the advantages of using the two materials in a composite system using shear stud connectors and, more recently, composite dowels.
What does the future hold for us? The future will likely be of prefabricated elements because they can be made of superior quality, where it is most cost-effective. The composite connectors may have application not only in the case of beam bridges but also in the case of cable-stayed or suspended bridges, gradually replacing the stud connectors. It is not possible to say exactly what the direction will be, but one thing is sure, the progress made so far in the field has been conditioned by the technology of execution, the quality of materials, the improvement of dimension methods, and the disposition of governments to invest. Certainly, these factors will further determine the progress in the field of steel-concrete composite structures used in the construction of bridges.

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