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Teil II
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Self-anchored suspension bridges with prestressed concrete deck: historic examples

Introduction

Manfred and I have some common interests, among which the history of concrete structures and for this occasion I have chosen a topic in this field. On 18 February 2016, Manfred received the Sarton Medal at Ghent University as a recognition of his unique and pioneering research work on the historic aspects of concrete structures and the link with modern strengthening and renovation techniques. At that occasion he presented a lecture on "What European History, Legendary Bridges and the Design of the Euro Have in Common", dealing with the different bridges appearing on the Euro bank notes. This paper deals with a challenging bridge type, which is not very well known: self-anchored suspension bridges with prestressed concrete deck. Some of these bridges were built in the 1950's over a canal around the city of Ghent after a design by Prof. Daniël Vandepitte (1922–2016). This paper is also a modest personal tribute to Prof. Vandepitte, who recently passed away at the age of 94 years and who was a brilliant teacher in structural analysis. He was a successor of Prof. Gustave Magnel (1889–1955) in the field of structural analysis and he designed several remarkable bridges in the early 1950's before he was appointed at Ghent University.

General concept and survey of existing bridges

The principle of self-anchoring eliminates massive anchorage structures, which have to withstand large horizontal forces, and which are necessary for classical suspension bridges. Instead, the cables are secured to each end of the bridge deck, which resists the horizontal component of the cable ten-

Fig. 1
Self-anchored prestressed suspension bridge with a central span of 100m at Merelbeke near Ghent
(Photo: collection Department of Structural Engineering)

sion. Therefore, the end supports resist only the vertical component of the cable tension, an advantage where the site cannot easily accommodate external anchorages [1].

Because the stiffening girders support the cable tension, these girders must be placed before the main cable can be erected. This construction sequence, which is opposite of that of a conventional suspension bridge, limits the self-anchored form to moderate spans and suitable site conditions [1].

Vandepitte [2], [3] points out that when the concept of self-anchoring is applied to a steel bridge, a considerable amount of additional steel is required in the superstructure as compared to that of a true suspension bridge in order to enable the stiffening girders or trusses to resist the thrust as well as the bending moments without being endangered by instability. The large thrust produced in the suspended bridge deck is, on the contrary, highly beneficial in the case of a concrete deck, for it acts as a prestressing force in the stiffening beams and helps them to withstand the bending due to live load. In the concrete case, instability is normally not a problem of any consequence, owing to the cross-section being naturally more sturdy than that of a steel suspended structure. For the same reason, a prestressed concrete suspension bridge is much stiffer than its steel counterpart and aerodynamic instability is also much more unlikely. However, most of the self-anchored suspension bridges have a steel deck, as the advantage of the absence of massive anchorage blocks apparently predominates the mentioned disadvantages.

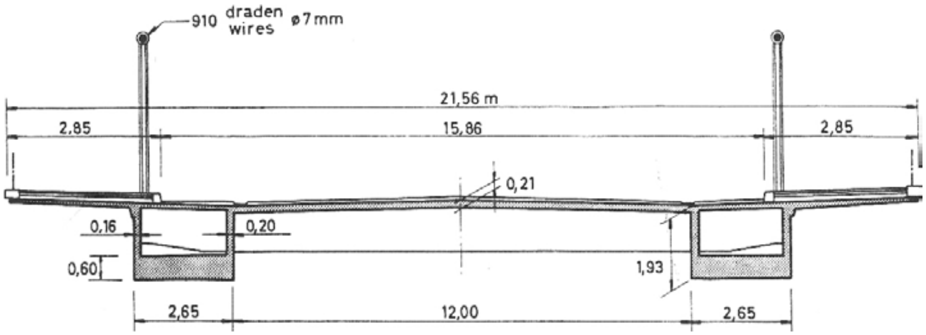

Fig. 2
Cross-section of the bridge deck
(taken from [2])

Although the concept of was mentioned for the first time by Langer in 1859 and independently by Bender in 1867, it became common in Germany in the beginning of the 20th century only [1]. The first large scale self-anchored suspension bridge, built over the Rhine river in Köln-Deutz with a central span of 185 m, was finished in 1915. The most notable of the German self-anchored bridges was the *Mülheimer Brücke* in Cologne (1929) with a central span of 315 m, which was destroyed in 1945. In the United States, three nearly identical bridges were constructed over the Allegheny River in Pittsburgh from 1925 to 1928. In 1955, the bridge in Duisburg with a span of 230 m was completed. Completed in 1990, with a main span of 300 m, the Konohana bridge in Osaka is the first large-scale, self-anchored suspension bridge built for vehicular traffic since 1955 and points to a renewed interest in this bridge type. In addition to its self-anchoring, this bridge is the first large-scale monocable suspension bridge, with the main cable and inclined hangers aligned in a single vertical plane in the centre of the road way. Very similar is the Yong Jong bridge near Seoul (2001), having the same main span length and A-shaped towers. It is the first combined road and rail bridge of its type and has a sag to span ratio of 1:5 compared to 1:6 for the Konohana bridge [4]. These ratios are considerably greater than those of externally anchored suspension bridges, which typically are around 1:10. These more recent bridges show that for spans on the order of 250–400 m, three span-self-anchored suspension bridges can offer a competitive design solution, while maintaining a traditional suspension appearance [11]. The San Francisco Oakland Bay Bridge, opened for traffic in 2013, is the largest single tower self-anchored suspension bridge in the world, with a main span of 385 m.

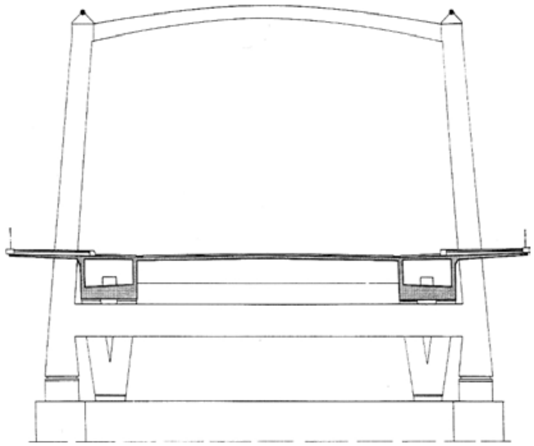

Fig. 3 Front view of a tower and cross-section of bridge deck (taken from [2])

All the previous examples are bridges with a steel deck. However, the self-anchored suspension bridge can also be obtained from a conventionally post-tensioned concrete bridge deck where, instead of keeping the tendons inside the concrete section, the tendons leave the girders [2], [3]. This allows to obtain significantly larger eccentricities which leads to a more economical solution in case of significant dead weight. The hangers provide the connection between the suspension cables and the bridge deck and transmit the upward forces created by the curved cables to the bridge deck.

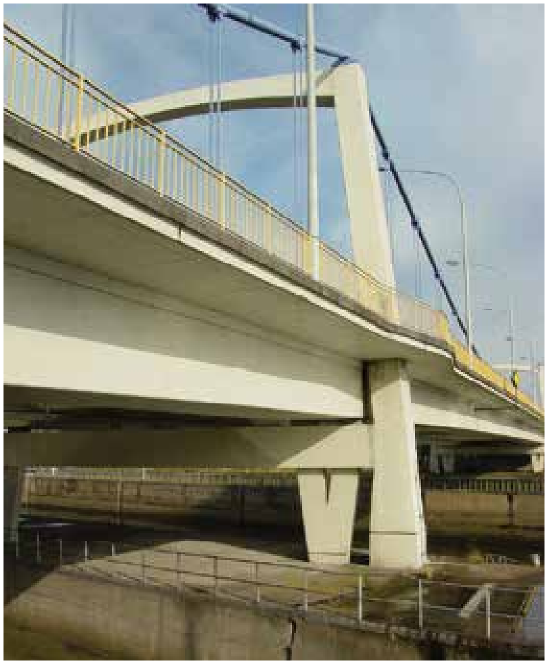

Fig. 4
Lateral view on one of the towers and V-shaped bearing walls (Photo: Luc Taerwe)

Fig. 5
Freyssinet hinge at lower part of V-shaped bearing wall (Photo: Luc Taerwe)

The first self-anchored suspension bridge with a concrete deck was built in 1950 at Saint-Germain-au-Mont-d'Or (France), with a main span of 57.9 m and side spans of 21.8 m, very similar to the bridge W13 which is discussed in the next section. As far as we know, Vandepitte was not aware of the existence of this bridge.

Jörg Schlaich and his partners designed several remarkable self-anchored pedestrian bridges throughout Germany, [5].

Original projects in Belgium

Vandepitte designed three self-anchored prestressed suspension bridges with a concrete deck of various spans over the ring canal around the city of Ghent between 1954 and 1964. This section mainly deals with one of these bridges.

The bridge in Merelbeke (designed as W12), shown in fig. 1, was finished in 1964 and has a

Fig. 6
Jacking up of the towers and positioning of the supporting concrete block
(Photo: collection Daniël Vandepitte)

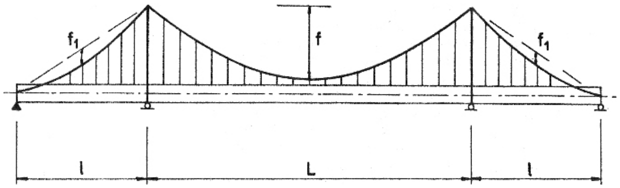

Fig. 7 Cable geometry (taken from [8])

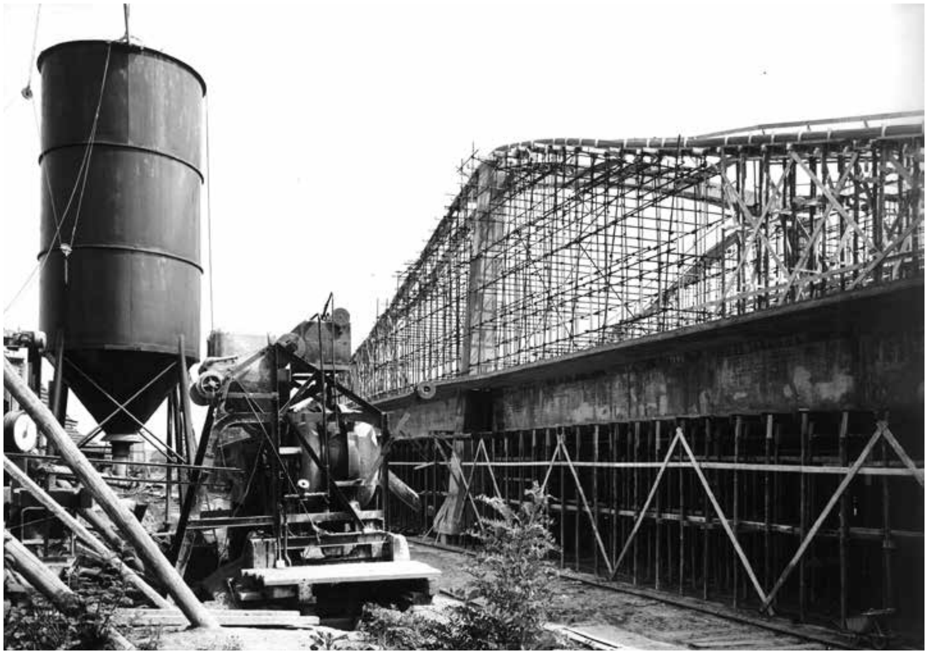

Fig. 8 Scaffolding of the bridge deck and the cables
(Photo: collection Daniël Vandepitte)

central span of 100 m, a total length of 192 m and the suspended structure is 21.6 m wide [2], [3], [8]. A cross-section of the bridge deck is shown in fig. 2.

Each of the main cables consists of 910 parallel galvanized steel wires 7 mm in diameter. The sag of the cables in the central span equals 9 m which corresponds to a sag to span ratio of 1/11.1, which is smaller than the ratios mentioned before for the steel bridges. The two stiffening girders are continuous box girders with a constant depth of 1.93 m which corresponds to 1/52 of the central span length. These girders are prestressed by the action exerted by the suspension cables only. There are no prestressing tendons in the suspended structure itself, which is independent of the towers. The tensioning of the cables and consequently the prestressing of the superstructure was achieved by jacking up both towers with respect to the piers, which was a quite audacious and spectacular operation.

The two cables are supported above each pier by a tower consisting of two legs, a flat arch connecting their tops, and two coupling beams connecting them underneath the roadway (fig. 3). On top of each leg, a cast iron saddle is positioned. The towers are wholly independent from the roadway structure and from the V-shaped bearings connecting the deck with the pier (fig. 4). These V-shaped bearings consist of concrete walls which have Freyssinet hinges at both ends (fig. 5). They are located in between the two coupling beams with sufficient spacing.

The plane of the hangers and the cables almost coincides with the plane of the outer webs of the box girders. The distance between the hangers equals 5 m. At each of these locations, a transverse beam is positioned below the bridge deck (fig. 2). These transverse beams are partially prestressed, which was not a common technique at that time.

Each tower was cast 0.67 m below its final design position, before the main cables were built up, wire by wire, without any tension and were connected to the concrete structure at their ends by means of the cable bands and of the hangers. Prestressing of the superstructure was achieved by jacking up both towers (not the roadway structure) with respect to the piers. Hydraulic jacks placed under the tower legs were used for that purpose (fig. 6). The jacking forced the cables to elongate and hence tensioned them, and it simultaneously

Fig. 9
First self-anchored suspension bridge (W13)
(Photo: Luc Taerwe)

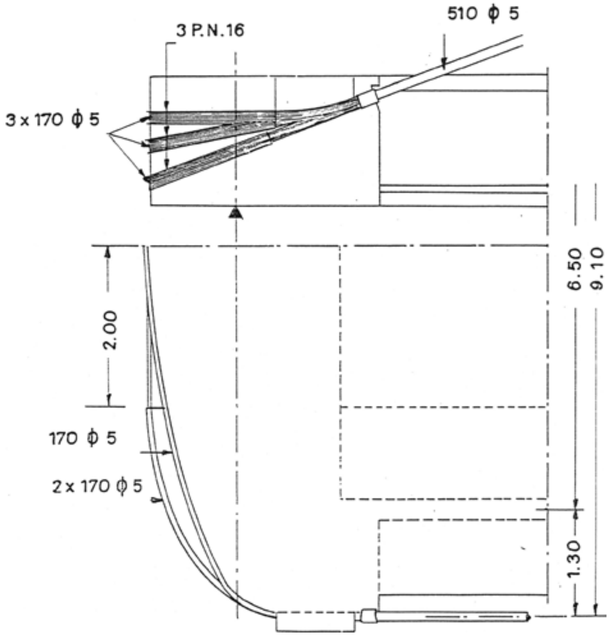

Fig. 10
Deviation of the continuous cable at one of the ends of the bridge deck: lateral and plan view (bridge W13)
(taken from [7])

Fig. 11
Bridge W16 at Mariakerke (Photo: Luc Taerwe)

produced a total prestressing force of 43.9 MN in the longitudinal girders, for which a lifting force per tower leg of 17.5 MN was needed.

In fig. 6, the positioning of the final supporting block is also shown. The top surface of this block is slightly rounded and serves as the lower part of the Freyssinet hinge located at the bottom of the tower leg (slightly visible in fig. 4). The mortar layer between the top part of the concrete block and the bottom part of the leg measures 135 cm by 38 cm. The locally wider part at the bottom of the tower legs, which was necessary to position the jacks, was removed after the jacking operation.

At the abutments, the horizontal component of the cable force is transmitted to the longitudinal girders as prestressing force, but its vertical component also needs to be resisted. This is achieved by fixing a concrete box filled with sand, below the transverse end beams.

The sags f and f_1 of the parabolic cables in the central span and lateral spans respectively were chosen such that $f/L^2 = f_1/l^2$ with L and l the corresponding span lengths (fig. 7). This means that the upward force per unit length exerted by the cable on the bridge deck is constant over the full length of the bridge. As this load was chosen to be initially 19 % higher than the dead weight of the bridge deck, upward reaction forces occur at the bridge piers under certain loading arrangements. Hence, the V-shaped bearings, mentioned before, were post-tensioned vertically to compensate the tensile force created by the negative support reaction.

The effect of the increase in tendon force ΔP in a regular prestressed concrete beam due to the deflection generated by live load is generally neglected. However, in the case of a self-anchored suspension bridge, where the cable has a large eccentricity, this beneficial effect is not negligible. Denoting by f the cable sag, the additional moment generated by the cable force increase ΔP equals –f. ΔP which reduces the positive beam moment due to live load. For the bridge W12 under consideration, the reduction of the bending moment at mid-span due to the full live load is 9.6 %. For other cable and bridge geometries, this reduction can be substantially higher.

The concrete bridge deck was cast on scaffolding over its full length (fig. 8), which was obvious giving the particular situation that the canal to be bridged was not yet dug at the time of construction. As this situation is not common, this bridge type has not been widely used. Moreover, in the 1960’s cable stayed bridges came into use, which turned out to be more efficient in construction.

Fig. 12
Lower part of one of the piers of bridge W16
(Photo: Luc Taerwe)

Fig. 13 Xiaolongwan Bridge in Nanjing (P.R. China)
(Photo provided by Zhao Liu)

The bridge W12, discussed so far was the third one in a series of three. The first bridge of this type (designated as W13) that was built over the ring canal in 1954–1955, had smaller spans: a central span of 56 m only and two lateral spans of 18 m. In the lateral spans no hangers are present and the cables are straight (fig. 9). This and the following bridge have in fact one continuous cable, which loops around the bridge deck at its ends (fig. 10). For this purpose, the cable is locally splayed out in three parts and deviated in the vertical plane by means of a concrete deviation saddle. As the friction between the curved cable parts and the bridge deck was released shock wise during the tensioning operation, causing unexpected loud bangs, two separate cables were applied in the third bridge W12.

The second bridge in the series (designated as W16), which was finished in 1958, is located in Mariakerke and has a central span of 100 m and lateral spans of 40 m (instead of 46 m for the bridge W12). In fig. 11 it can be noticed that the hangers are anchored in the ends of the transverse beams, which protrude from the bridge deck. This is not the case for bridge W12 (fig. 1) where the lateral view shows a continuous box girder, which is aesthetically more pleasing. Fig. 12 shows the lower part of one of the bridge piers where the lower flange of the I-shaped stiffening girder can be noticed. Below the legs of the towers, steel hinges are provided and the steel rods which are visible besides the vertical wall supports have to resist the upward reaction force, while the walls resist the downward reaction force. As mentioned before, in bridge W12 the post-tensioned wall supports can resist both positive and negative reaction forces.

Applications in China

According to personal contacts, many self-anchored suspension bridges with prestressed concrete deck have been built in China. The first one is Jinwan Bridge in Dalian (2002), with a total length of 198 m and the length of the main bridge being 24 + 60 + 24 m.

Recently, the attention of the author was drawn to the Xiaolongwan Bridge (2013) in Nanjing, shown in fig. 13, which is of the same type and has with 44 + 96 + 44 m similar span lengths as the bridge W12 in Merelbeke. However, in this case the cables were stressed by tensioning the hangers, as was performed at San Francisco's Oakland Bay Bridge, in combination with a stepwise pushing up of the saddles [5].

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