The Development of the Prestressed Concrete Bridge in Germany after World War II

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SUMMARY

The success of prestressed concrete bridges in Germany began with the first pilot projects before World War II. After the war, 20 years were sufficient for the bridge to dominate the market. Six nuclei made vital contributions to the success of the prestressed concrete bridge.

A detailed description of the early years of constructing bridges out of prestressed concrete makes it possible to simply describe later periods in systematic outline. Social influences will be touched upon and will help illustrate road construction as an impulse generator for prestressed concrete.

INTRODUCTION: THE PERIOD OF FOUNDATION AND INNOVATION BEFORE 1945

Between 1886 and 1906, the idea of prestressing concrete was formulated (Leonhardt 1962, pp. 625-626). Based on the extreme elastic deformation of the vertex of the Pont de Le Veudre sur l'Allier in 1912, Eugéne Freyssinet (1879-1962) inferred the non-elastic deformation habits of concrete and the necessity to use high-strength steel to prestress the concrete (Freyssinet 1949). Interrupted by World War I and running projects, Freyssinet used the depression between 1926 and 1929 to develop all essential prestressing equipment. By embedding the tendon in the concrete, Feyssinet liberated the concrete from the necessity to form an arc, thereby defining the form of the prestressed concrete bridge right from the start. Prestressed concrete found its way to Germany with the help of Dr. Karl Mautner (1881-1949), board member of the Wayss & Freytag A.G. and professor at the Technical University in Aachen. Germany found its own way to show gratitude towards its Jewish citizen (Grote and Marrey 2000, pp. 26-31 and 38-42).

The cooperation between Freysinnet and the German engineers of Wayss & Freytag resulted in the farm track bridge near *Oelde* (span l = 33 m; construction depth h = 1,60 m) on the Autobahn between Dortmund and Hannover 1938, which was the successful pilot project for the time after 1945 (Metzler 1999, pp. 153-159). Its four beams, precast in a stressing mould, their tensioning wires internal bonded, pointed the way towards the rules of prestressed concrete as they are still valid today. It was followed in 1942 by the Autobahn bridge across the Glatzer Neisse near Breslau in today's Poland (l = 42 m).

Grote and Marrey (2000, pp. 58-68) points out four other bridges outside Germany built according to Feysinnet's method. Among them is the trial bridge (l = 10.5 m) near Elbeuf, completed in 1942, which brought Freysinnet closer to his ideal of completely avoiding cracks through three dimensional prestressing. Equipped with his newly developed concrete cone anchoring, Freysinnet, in Elbeuf, conducted longitudinal curved tendons in accordance with the dead load, for the first time realizing post-tensioning. In addition to this, he gave the bridge a transverse prestressing. In accordance with his contract, he shares his knowledge with the engineers of Wayss & Freytag.

In contrast, the viaduct at *Aue* with its external tendons made from higher-strength construction steel St 52, remained an isolated case. Franz Dischinger (1887-1953), chief engineer at Wayss & Freytag's competitor, the innovative construction company Dyckerhoff & Widmann A.G., was too careful when it came to the new high-strength steel and higher-strength concrete. The prestressing he applied disappeared nearly completely from the haunched superstructure, as a result of creeping and shrinkage of the concrete. The viaduct at Aue (l_{max} = 69 m) indicates the state of knowledge before Freysinnet's collection of patents (Schönberg and Fichtner, 1939).

The overpass near *Wiedenbrück* (l = 35 m, h = 1.82) not far from Oelde, executed with the autonomous prestressing of Ulrich Finsterwalder (1897-1988), who was at the time an associate of Dischinger's, also remained an isolated case. Finsterwalder developed Dischinger's ideas further (1938, pp. 495-499), letting the prestressing of high-strength tension rods be created by the superstructure itself. Its polygonal underspanned, double webbed T-beam with parallel chords has a central hinge with a pressure slab and is prestressed as the two halves of the beam are lowered revolving round the central hinge.

The German pilot projects are rounded off in 1941 with the pedestrian overpass at *Berlin Tiergarten* (l = 22.5 m, h = 1.08 m). The engineers of Beton- und Monierbau could build on the knowledge base established by Dischinger and Finsterwalder. External, polygonal suspenders rest, via steel saddles, on five crossbeams. Oil compactors interposed between the saddles and crossbeams replace the central hinge and prestress the suspenders against the double webbed t-beam.

While the independent German pilot projects in external prestressing had reached an impasse in 1942, the adaptation of Freysinnet's prestressing technique enabled Wayss & Freytag to build up a technological lead for the start into freedom.

THE PERIOD OF ORIENTATION AND COMPETITION (1945 – 1965)

On April 25., US and soviet troops met on the steel bridge in Torgau. On May 23. 1945, the allied forces ended the national socialist rule of terror – the zero hour in Germany. Millions of people had been uprooted and wandered aimlessly and homelessly through Germany. They encountered a fragmentary infrastructure, with no institution, such as building authorities or the construction industry, supervising building or repair. Even in the last weeks of the war, many bridges had been blasted at random and without military sense.

First the military government, then the appointed state governments in 1947 and finally the first elected federal government in 1949 also faced the task of restoring, as quickly as possible, the arteries of German traffic.

The military government and the locally appointed municipalities concentrated first on bridges across roads and rivers inside the town and city limits. These were restored with easily controllable construction methods, materials and reusable components found on site, usually from steel bridges. Permanent solutions were only sought as a second step. Overland traffic was handled by the railway system.

From 1947 on the state governments provided a lobby for inter-urban roads with regional connections. Only in 1949 were the building and operation of highways in Western Germany regulated through codification in the new Federal Republic's constitution (§ 90). A further seven years went past before the federal *Bundestag* passed the first requirement plant for the extension of federal highways, based on which the first concrete plans for the extension of the network of federal highways were assigned. It was the beginning of the construction of one of the biggest and most successful building projects in the world, the federal Autobahn system, which today has a length of approximately 12 000 km. While the railway system, because it was built up in the 19th century, still today carries the competitive disadvantage of an East-West orientation, the fact that the federal highways, for reasons of post-war politics, had a North-South orientation guaranteed the success of road traffic.

Between 1945 and 1949, Germany had to do some political soul searching and find the democratic way back into the community of states. In everyday life, new pragmatic solutions had to be found every day without too much bureaucracy and little administrative coverage. This time between political standstill and societal will to rebuild was a chance for the widely unknown prestressed concrete and explains its first thrusts of innovation. As a young technology, it lived without the corset of an excessive technical rules and regulations and was free of construction and assembly methods fixed by investment or capital assets. The difficulty of acquiring materials for high-strength steel and cement was no problem but challenge that drove the first German engineers to build with prestressed concrete to be more creative. In an absence of construction steel and a lack of skilled labour they saw a chance to establish the new construction method. They knew about the commercial superiority of their new construction material (Lämmlein and Wichert 1950a, pp. 66-68).

The development of prestressed concrete was boosted by innovative nuclei around the engineers of Wayss & Freytag A.G. and Dyckerhoff & Widmann A.G., construction supervisors in the developing building authorities not afraid to take risks, and creative consultant engineers, who used the time of standstill to gain new insights and make improvements (Leonhardt 1984, p. 156).

Up until 1950, six nuclei for the creation of the prestressed concrete bridge are discernible in Germany.

First nucleus: The engineers of Wayss & Freytag A.G. around the branch managers and students of Mörsch, Hermann Bay (1901-1985) in Hamburg (Stiglat 2004, p. 70), Karl Deininger (1896-1956) in Stuttgart (Stiglat 2004, p. 119) and the head of bridge construction Gotthard Franz (1904-1991) in Frankfurt (Stiglat 2004, pp. 148-152).

The engineers of Wayss & Freytag purposefully went about using their head start in knowledge dating from the years before 1942 and the acquisition of Freysinnet's patents in 1935 to acquire their first bridge construction projects. Equipped with both of Freysinnet's methods of prestressing, the older stressing mould process as well as the concrete cone anchoring for post-tensioning, they were able to execute designs intended for steel and reinforced concrete more cost-effectively in prestressed concrete.

Two bridges by Wayss & Freytag adapted the stylistic features of reinforced concrete. The *Herdbrücke* in *Ulm* (1948) across the Danube is a 59.2 metre wide internal-walled arch bridge with a rise of 7.73 metres. The walls cantilevered 7.8 metres back over the abutment and thereby ease the horizontal thrust. Between the abutments, the six internal walls are joined via the upper carriageway and the thrust slab to three hollow box girders. Rolling contact joints connect the vertex and the abutment (Kaiser, A and König 1950; Mörsch 1958, pp.437-440). The more delicate three-hinged frame of the *Neckarkanalbrücke* in Heilbronn (1949) achieved a span of 107.8 metres and had a rise of 11.15 metres. As in the *Herdbrücke*, the carriageway and thrust slab join the four frame slabs between the two frame abutment hinges into two hollow box girders. The frame cantilevered 11.8 metres inland over the abutment hinges and carry the side spans with a span of 21.3 metres (Stöhr 1950, pp.269-274 and 1951, pp.30-32; Mörsch 1958, pp.431-437). The internal walls of the *Herdbrücke* and the three-hinged frame of the *Neckarkanalbrücke* were prestressed on the top side to keep the tension in the concrete near the abutment small or eliminate it altogether. As they did not fully understand the mechanics of cracking yet, the engineers of the big reinforced concrete bridges like the *Alte Kanalhafenbrücke* in *Heilbronn*, built 1931 and destroyed in 1945, had been faced with big problems that prestressed concrete could solve.

Wires of 32 mm were used for prestressing. They were run loosely, un-galvanized and un-oiled, through special grooves and prestressed over steel traverses against the hardened concrete using hydraulic presses. While the tendons in the *Herdbrücke* at *Ulm* had been run straight, the tendons of the *Neue Kanalhafenbrücke* at *Heilbronn* already followed the distribution of moments in partially enclosed tension ducts. Immediately after prestressing, the tension ducts were filled with concrete. To avoid having to calculate losses through creeping and shrinking, the engineers included a flat adjustment of the steel tension by 18.75%. At the time of the first prestressed concrete bridges, this was a perfectly usual practice.

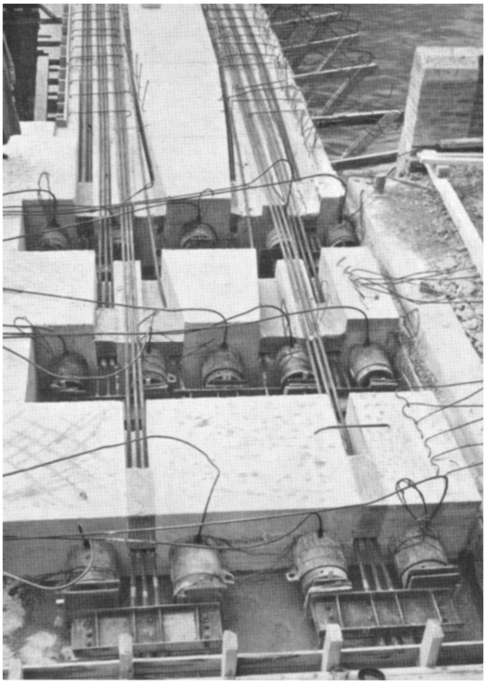

Figure 1. Pprestressing and prestressing jacks of the Herdbrücke in Ulm (Mörsch 1958, Abb. C 179)

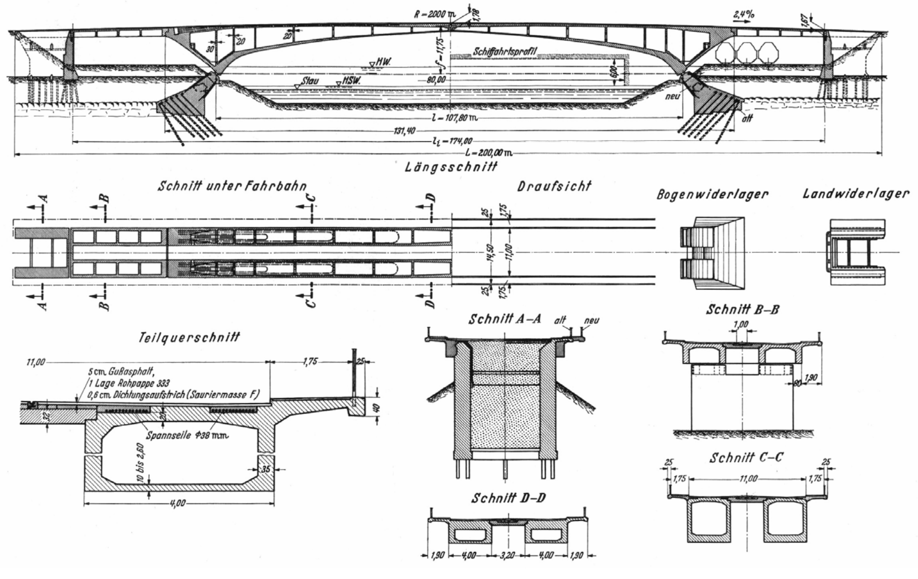

Figure 2. The neue Kanalhafenbrücke in Heilbronn (Mörsch 1958, Abb. C 173)

The new *Hinckeldey-Brücke* in Berlin (1952) was already a masterwork and an early culmination of prestressed concrete frame bridge construction. Three perpendicular, staggered two-hinged frames with massive frame leg and box girders span the *Hohenzollernkanal* at 63.2 m. Their Freyssinnetian tendons with sheats bent organically in response to the inner forces. Not quite in correspondence with the wishes of the French teacher, the bridge is fully prestressed only lengthwise. Crossways, the engineers set light tendons at intervals of about 48 cm into the carriageway layer, which they partial prestressed. The reinforcements of the frame legs reflect the resolved frame corners of Freysinnet's *Marnebrücke* (Mörsch 1958, pp. 274-281). The *Brücke am Gänstor* (1951) in Ulm, built nearly at the same time by Dyckerhoff & Widmann (Finsterwalder and König 1951), the *Rosensteinbrücke* in Stuttgart (1952) by Leonhardt, Andrä and Ludwig Bauer (Leonhardt and Bauer 1954) and the *Lombardbrücke* (1953) by Dyckerhoff & Widmann in cooperation with Wayss & Freytag (Mörsch 1958, pp. 287-291) all have resolved frame corners.

The frame bridges were the result of the need to restore traffic connections over rivers or canals without significant changes in road level. They had a continued and technically laborious later life in the strutted frames of early Autobahn overpasses. We will find these socially demanded structural systems formally echoed in the second phase of prestressed concrete innovation.

Figure 3. Fly over near Kirchheim

The patent for precast concrete elements, prestressed in a stressing mould, registered in 1935, and the knowledge gained in Oelde, translated into a competitive edge for the engineers of Wayss & Freytag when it came to the numerous smaller structures, underpasses and overpasses, which had to be rebuilt. The double span fly over of the A7 and A4 interchange near Kirchheim in North Hessia, rebuilt in 1949, is regarded as one of the first prestressed concrete constructions in the federal highway network. For each carriageway, the rather skewed crossway construction has a superstructure with a span of 23.5 m. Six prefabricated beams, which are prestressed on site, are lifted in for each of the four spans. The reinforced end and cross girder, the carriageway, and the precast concrete elements form a girder grid that replaces the destroyed steel superstructure from 1938 (Wolf 1950).

Second nucleus: The consultant architects Fritz Leonhardt (1909-1999) (Leonhardt 1984, pp. 156-165), Wolfhart Andrä (1914-1996) (Stiglat 2004, pp. 38-49) and Willi Baur (1913-1978) (Stiglat 2004, pp. 62-69) from Stuttgart.

In the summer 1948, chief planning and building officer Ernst Wahl from Koblenz made contact to Freysinnet for Fritz Leonhardt through visits to building sites at the Marne in Paris and finally in Grenoble. "These travels became the spur for me to begin my own developments in prestressed concrete" (Leonhardt 1984, p. 142). Leonhardt and the tinkerer Baur used wires from the destroyed suspension bridges on the Rhine as prestressing steel, converted *cooking pots* to hydraulic presses and realised their first project, the *Elzbrücke* at *Bleibach* (1949), a single span simply supported slab bridge. They had to be skimpy with prestressing steel and cement. In addition, the superstructure had to get by with a slenderness of 1/26.7, which illustrates the daringness of Andrä, the associate responsible for the calculations. The superstructure was lightened in the middle third through non walkable hollow blocks. A massive cantilever, hidden inside the box abutment, reduces the field moments by generating a moment of support (Lämmlein and Wichert 1949).

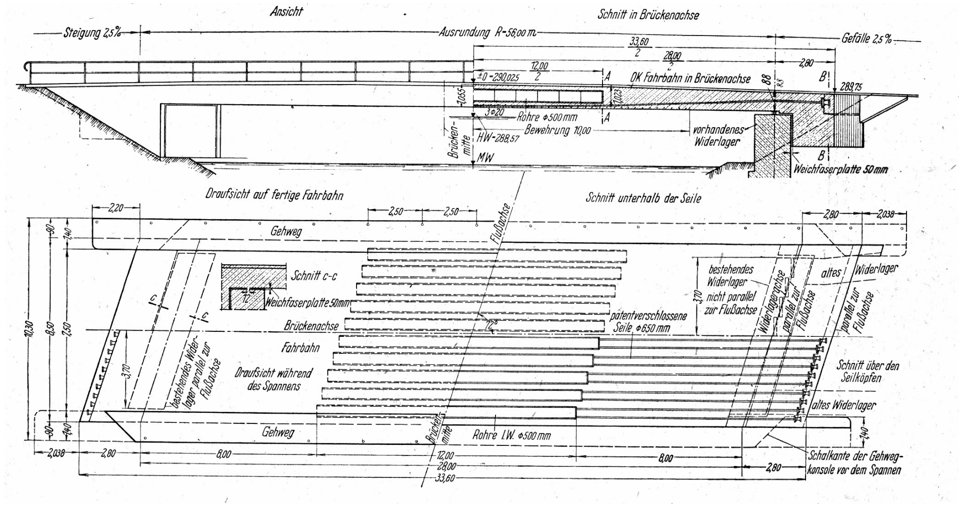

Figure 4. Elzbrücke at Bleibach (Lämmlein and Wichert 1949, Abb. 1)

The *Elzbrücke* in *Emmendingen* (1949), the second prestressed concrete bridge of the consultant engineers Leonhardt Andrä und Baurs, was a continuous three span haunched slab bridge with a span of 15.0 m + 30.0 m + 15.0 m. At an overall depth of 58 cm in mid span and 121 cm above the support, this massive superstructure was also very slender.

Figure 5. Elzbrücke in Emmendingen (Mörsch 1958, Abb. 97)

For the Elzbrücke, the cooking pots had already been developed into the prestressing method using concentrated tendons, later known as the Baur-Leonhardt prestressing method. In prestressing method, a large number of strands were protected from the concrete inside metal boxes to reduce friction and redirected at pre-cast, half-cylindrical chuck heads. The press- or cooking pots where incorporated between the end of the superstructure and the chuck heads. After the concrete had reached the required strength, the superstructure was prestressed by extending the cooking pots simultaneously. Subsequently, the cooking pots remained enclosed in the concrete of the construction. Later, special presses with tensioning load of up to 5 MN, which could be dismantled afterwards, replaced the cooking pots of the early years after the war. The *Elzbrücke* at *Emmendingen* is the first continuous prestressed concrete girder bridge (Lämmlein and Bauer 1950) with continuous tendons and bond.

In 1950, it was followed immediately by the analogous construction of the first German prestressed concrete bridge for train load, the railway bridge across the Neckar canal near Heilbronn.

With the monolithic *Neckarbrücke* at *Neckargartach* (1951), which traverses 225 m (Mörsch 1958, pp. 190-193), and the *Donaubrücke* at *Untermarchtal* (1953), whose spans of 62.0 and 70.0 build up to a total length of 375 m (Leonhardt 1953a), the paradigm of the German road girder bridge had been found. Both have been realised according to the Baur-Leonhardt method. The *Neckarbrücke* traverses the river with five openings with a span of 43,5 m each, and two parallel boomed hollow box girders at a depth of 1,80 m. Free of the requirements towards a road clearance, the *Untermach* valley can be spanned with a double-webbed T-beam with slender web of 4.05 m height. Cross beams at every third of each span guarantee a sufficient distribution of the load. The traverse spanned and subdivided carriageway slab has been prestressed with narrowly laid, light *Leoba* tendons. The *Neckarbrücke* was completely formed, due to their tendons running through the whole length of her superstucture. The superstructure of the *Donaubrücke* was subdivided into two sections by overlapping the concentrated tendons longitudinally. So Leonhardt cut down successfully the cost of the erection of the superstructure. The shift towards problems of the construction process signalised the beginning normalization in the building of prestressed concrete bridges.

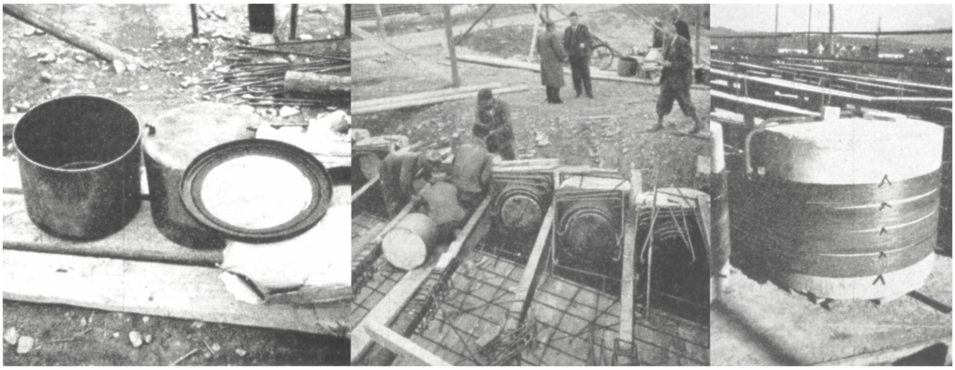

Figure 6. Cooking pots and chuck heads before and after installation into the Elzbrücke at Emmendingen (Lämmlein and Bauer 1950, Abb. 7-9)

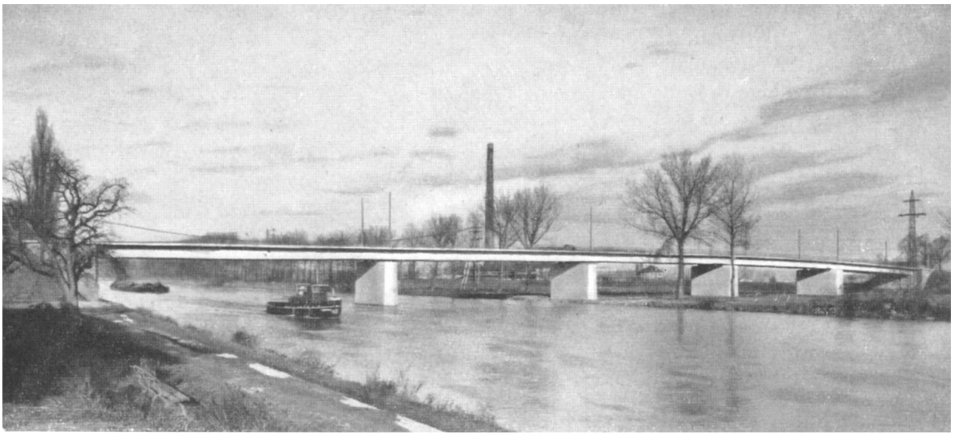

Figure 7. *Neckarbrücke* at Neckargartach (Mörsch 1958, Abb. 261)

Fritz Leonhardt und Willi Baur developed another successful prestressing method, namely the *Leoba* tendon, originally intended to complement the concentrated tendons, to be used for lighter loads, needed in building construction and for the traverse prestressing of carriageway slabs (Leonhardt 1953b). Willi Bauer later extended his method to higher prestressing loads. This solution, which was of high technical quality and yet simple, displayed all components of today's post-tensioning methods. A helix carefully distributes the force that needs to be anchored. Sheat and bleed openings serve to help prevent corrosion of the prestessing strands with grout mortar.

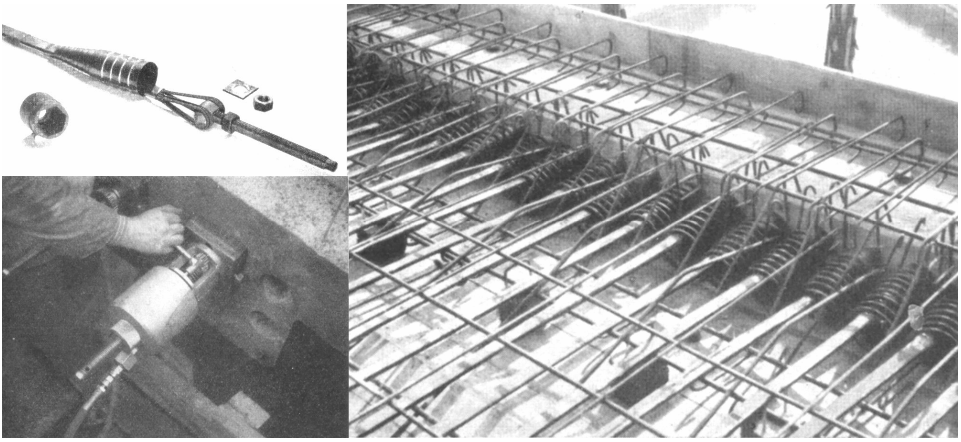

Figure 8. The Leonhardt prestressing method (Leonhardt 1953, Abb. 5 und 9)

Leonhardt though beyond the purely technical solutions. In contrast to the big construction companies, which sought, through patenting, to become the sole users of their knowledge about prestressed concrete, Leonhardt released his prestressing method to make it accessible for the smaller building companies. These could bid very cost effectively because of low overheads, and had a more technical orientation. After buying the complex prestressing techniques, they concentrated on formwork and reinforced steel and constructed bridges of high quality. The early small business owners F. X. Stichler in Freiburg, Ludwig Bauer in Stuttgart, and Wolfer and Goebel in Esslingen can be seen as representative. They made Leonhardt's first prestressed concrete bridges reality. This holistic approach was the key to the success of prestressed concrete bridge construction.

Third nucleus: Ulrich Finsterwalder, chief engineer of Dyckerhoff & Wiedmann Berlin München (Stiglat 2004, pp. 145-146)

After the failures of external tendons using normal higher-strength bars of steel grade St 52, Finsterwalder found, in the hot rolled steel St 60/90 and later 60/105 of the smelting works Krupp Rheinhausen, the appropriate steel for his prestressing bars. At nearly twice the tensile yielding strength, the steel was unsusceptible to brittle fracture and stress corrosion. Finsterwalder succeeded of rolling a thread onto the 26 mm strong bars and so make them suitable for connection and anchoring. A single bar had a bearing capacity of approximately 0,3 MN, which was about the bearing capacity of the early Leoba tendons.

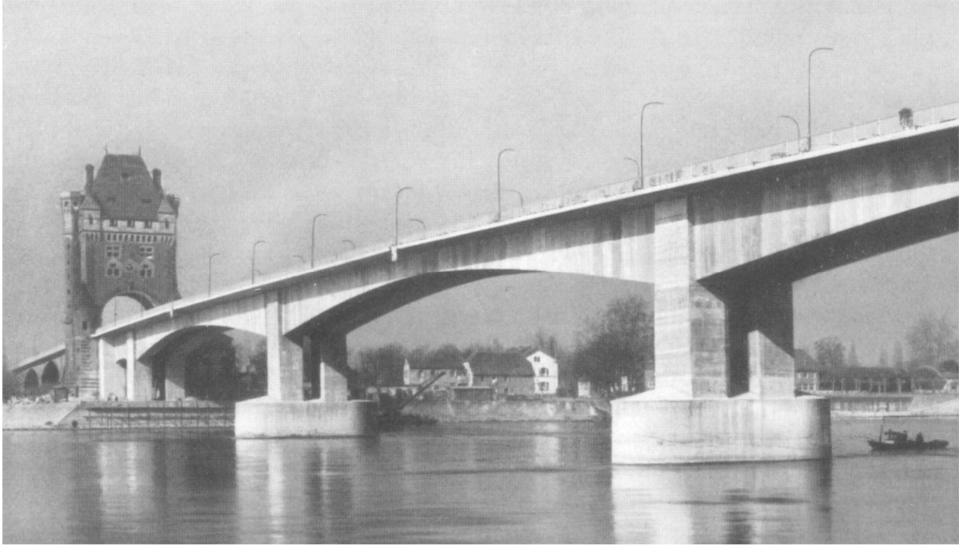

Figure 9. View of traffic on the Nibelungenbrücke in Worms (Wahl 1953)

Finsterwalders single bars had the advantage that there was nearly no slipage and hence nearly no prestressing loss on removing the prestressing jack, which made them suitable for little elongation stretching, too - which was a prerequisite for cantilevering construction with short sections. Finsterwalder was known as a designer who wasn't afraid of risks. Before one could building the *Nibelungenbrücke* across the Rhine, Ernst Wahl, chief planning and building officer of Rhineland-Palatinate from Koblenz, had Finsterwalder test the cantilevering construction in prestressed concrete by building a bridge across the Lahn near Balduinstein (Finsterwalder 1952, p. 153 and Wahl 1951). The *Lahnbrücke* with a span of 62 m thereby became the first prestressed concrete bridge in the world built as a cantilevering construction. The final bridge is a suspended double webbed T-beam with abutting ends, which bring down the field moments of the bridge through concrete weights. During the cantilevering construction work, the bridge rested on abutments and counterweights, which had been concreted onto the subsoil. Before the concreting of the final segment at the centre of the bridge, the counterweights were lifted by presses. The change in system from a cantilever to a single span girder made a two separate layer of tendons necessary.

After the successful construction of the *Balduinbrücke* and a further pilot project, the *Neckarbrücke* at *Neckarems* (Finsterwalder 1952, p. 154), Wahl could tackle the replacement of the steel arch bridge in Worms, which had been destroyed in World War II, with the help of Finsterwalders cantilevering construction, which, in competition with steel bridge construction, proved to be more cost effective. Bound to the position of the piers of the destroyed steel bridge, the road bridge at Worms later to be called *Nibelungenbrücke* spans the Rhein in three spans of 101.65 m + 114.20 m + 104.20 m. The superstructure is a system of cantilever beams which are connected among each other with prestressed hinges made of steel casting roller bearings. Two hollow box girders with an depth of 6.5 m at the pier cut and 2.5 m in mid span were connected through the carriageway slab and formed the superstructure of 13.5 m width. The parabolically curved lower edge of the superstructure followed the power flow of the cantilevering construction. The reinforced hollow box piers and the superstructure are monolithically connected.

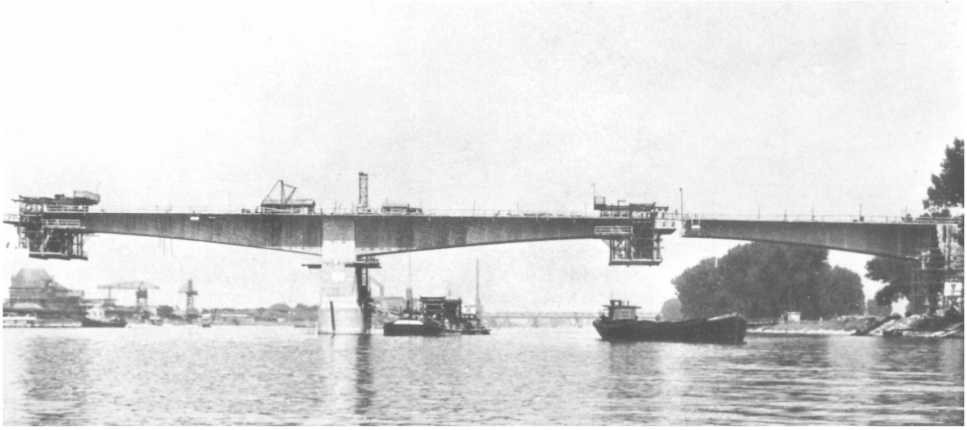

Figure 10. Cantilevering construction of the *Nibelungenbrücke* in Worms (Finsterwalder and Knittel 1953, Abb. 16)

The superstructure grows out of the centre piers simultaneously on both sides, rising in sections of 3.0 m towards mid span, thereby keeping small the difference moments working on the subsoil, while the end piers had to be weighed or hung back from the rising superstructure in order to control the tip moment. This was helped by the existing foundations, which had absorbed the horizontal thrust of the destroyed steel arch bridge. Finsterwalder used his proven single bars St 60/90 for prestressing. He adjusted the tendons of the superstructures, which cantilevered up to 57.1 m, strictly to fit the trajectories of the principal tensile stress, and he gradually decreased them towards mid span, in line with the decreasing bending moment. Under full load and in given an inconveniently positioned traffic load, Finsterwalder allowed for a tension wedge, and this was later called partial prestressing. 486 bars with a diameter of 26 mm were necessary in order to be able to resist the fixed-end moment of the full load at 446 MN m at the centre piers. Their original eccentric pressure force of 108 MN fell victim to creeping and shrinking loss of 20 MN. At the end of each section about 24 bars were prestressed and anchored (Finsterwalder and Knittel 1953). The concrete grade of B 450 was a technical but also a logistic challenge in the years after the war. After 22 months of construction the bridge was opened to traffic on April 30. 1953.

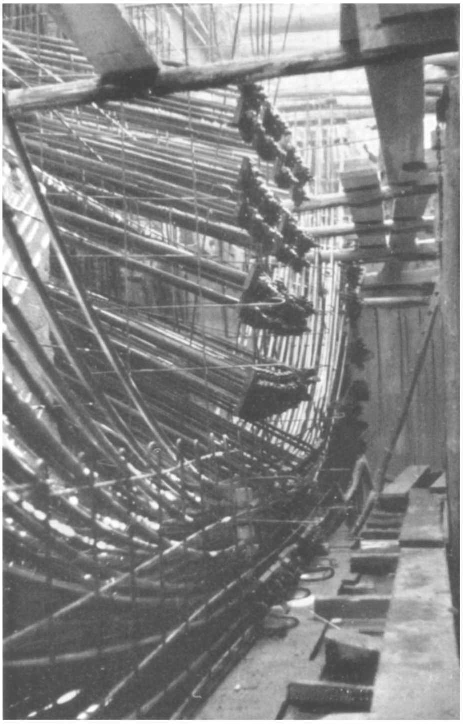

Figure 11. View into supporting cross girder with prestressing bars of the *Nibelungenbrücke* in Worms (Wahl 1953)

With the *Nibelungenbrücke* at Worms, the technological advantage of Wayss & Freytag against Dyckerhoff & Widmann was gone. The *Nibelungenbrücke* was Ulrich Finsterwalder's early and lasting masterpiece. In the course of only five years, prestressed concrete began to displace steel from its domain in high bridge building. In 1964 Herbert Schambeck (Stiglat 2004, pp. 359-367), Finsterwalder's student, decided the race for the construction of large girder bridges in favour of prestressed concrete with the construction of the *Rheinbrücke* at *Bendorf*, spanning 208 m (Finsterwalder and Schambeck 1965).

Fourth nucleus: The innovative owners in southern Germany

Any nucleus that is supposed to germinate needs fertile ground, space to grow in, and a supportive and guiding hand. In southern Germany the first engineers of prestressed concrete encountered owners who were competent and willing to take risks, and who were faced with a shortness in the steel supply, staff and money shortages and had the job of giving Germany a functioning infrastructure once again.

Government building officer Willi Stöhr, from the school of the reinforced concrete pioneer Karl Schächterle (1870-1971) (Stiglat 2004, p. 358), who had been responsible for supervising construction of the *Herdbrücke* in *Ulm*, relocated to Heilbronn and here initiated early use of the cost effective prestressed concrete in the bridges *Obere Badstraße, Neue Kanalhafenbrücke* and *Neckargartach*. He convinced federal rail official Klett to build Germany's first railway bridge constructed with prestressed concrete in Heilbronn (Leonhardt 1984, p. 161). Hermann König created the prestressed concrete frame bridge in Ulm. Arthur Lämmlein from Freiburg, together with local construction companies, gives the engineers around Fritz Leonhardt the space to realise the first prestressed concrete beam bridges in *Bleibach* and *Emmendingen*.

Ernst Wahl from Koblenz, chief planning and building official in Rhineland-Palatinate, met Fritz Leonhardt during the reconstruction of the Moselbrücke, which had been destroyed during the war, (Leonhardt 1984, p. 142). He supported Ulrich Finsterwalder in the crossings of Mosel and Rhine, and in turn was given cantilevering construction.

Probably more personalities can be discovered. For example, early prestressed concrete bridges can be found in the area around Kassel or Hamburg/Rendsburg, usually going back to secondary tenders by Wayss & Freytag, which would not have come about without competent owners. The fear of revealing competitive advantages "traditionally means that corporate engineers remain anonymous" as Gotthard Franz in Stiglat (2004, p. 149) regrets, and this still keeps the name of many a creative engineer from us even today.

For the engineers on the owner side, prestressed concrete was at first simply a cost effective building material, assumed, according to Freysinnet, to be free of cracks, and providing long lived and low maintenance constructions of high quality. But they also knew that the sober prestressed concrete was the expression of a new time (Wahl 1953).

Fifth nucleus: Hans Wittfoht, engineer for Polensky und Zöllner (Wittfoht 2005), complemented by the engineers of STRABAG Bau-A.G.

In the mid-1950s, a new community of engineers grew in STRABAG Bau-A.G under the influence of Hans Wittfoht, the chief engineer of Polensky und Zöllner (PZ) in Köln. In 1949 Helmut Homberg (1909-1990) (Stiglat 2004, pp.189-193) had shown how to calculate a skewed bridge using a simplified grillage calculation. Wittfoht took this approach further and designed prestressed-concrete bridges that can be made to follow the alignment of any road in both plan and elevation, an advantage that bridges made of steel or composite construction do not have. As Wittfoht remarked "Prestressed concrete is the basic building material of our time, because it can be formed and adapted and is cost effective. The advantage lies with those who are creative" (Stiglat 2004, p.453). Wittfoht's own creativity unfolded in response to specific construction challenges; working on live projects all the time left him with no time to reflect at leisure on unsolved problems.

The bridge at *Hohensyburg* is part of a road that crosses back under itself in a loop, in order to reach the bottom of the Ruhr valley. To follow the course of the road, the superstructure needed a horizontal curvature radius of 36 m. Wittfoht chose a slender plate, 65 cm thick, which he supported at the points one third and two thirds along with traverse frames. The 88 tendons of the patented prestressing technique PZ, each with a bearing capacity of 0.4 MN, followed the curvature radius horizontally. Vertically they were placed, following tradition, in line with the diagram of moments, to reduce permanent load. The different elongation values for inner and outer edge, resulting from the strong curvature in the ground plan, arose as calculated (Wittfoht 1956 and Wittfoht 2005, pp. 25-28). Further buildings with free ground plans followed. Only in 1963, however, did Wittfoht find the time to combine the experience gained in the construction of curved one- and multi-span bridges, and to hand in the general solution as a PhD thesis, and later publish it as the standard work on bridge construction (Wittfoht 1964).

Figure 12. The bridge at Hohensyburg (Wittfoht 1972, Bild 204)

The expansion of the Autobahn network all over the country, decided on by the Bundestag in 1956 in order to satisfy the needs of the rapidly growing private traffic, focused engineers on rational construction methods. The location of the Autobahn virtually negated the topographical conditions and instead tried to optimize the economic effort of vehicle and road. These requirements cause the construction of a large number of mighty viaducts, and tempted the big construction companies to invest in fully mechanized, manoeuvrable falseworks, probably also thinking that, because of the huge necessary investments, they would be able to share the market in road construction amongst themselves.

Wilhelm Klingenberg, deputy assistant under-secretary and responsible for bridges in the course of federal highways, skillfully used the construction of the federal highways 9 near Andernach and Neuwied, in order to find, through the competition between the construction companies Polensky and Zöllner and STRABAG, the best solution for a mechanise construction method that would lead to shortened construction times. Both companies were led in their development towards a steel falseworks clear of the ground and spanned the whole span of the bridge, and which clocked the construction strictly into the sections reinforcing, concreting, prestressing, changing over and moving forward. They separated the cantilevered falsework into the actual service girders, the steel nose, measuring about 1.6 times the span of the bridge, which has the job to move the falsework onto the next span, and the support construction.

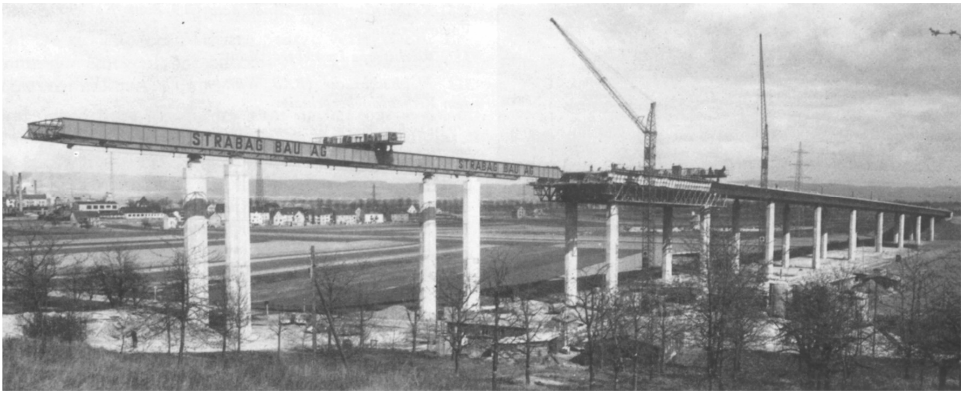

Figure 13. The bridge at Kettiger Hang (Wittfoht 1972, Bild 314)

The bridge at *Kettinger Hang*, approximately 508 m long, contracted by STRABAG, was opened to traffic in 1960. Its continuous superstructure was separated into 13 equal spans, each 39.2 m wide. The parallel boomed superstructure had two hollow box girders as main girders with a construction height of 2.10 m. It was prestressed longitudinally and transversally. The alignment of cross girders is limited to the support axes (Gass 1960). Hans Wittfoht only succeeded in finishing his 1080 m long *Krahnbergbrücke* in 1964, though it had been projected at the same time. Like the Kettinger Hang, the bridge separates a length of about 1080 m into 34 equal spans of 31.75 m. The bridge was strongly curved in its ground plan, and this made necessary a double-celled hollow box girder with partial longitudinal and transversal prestressing and a depth of 2.0 m. By relinquishing the separation of the service girders, Wittfoht simplified the STRABAG cantilevered falsework into a one phase system (Wittfoht 1965).

The high investment costs of cantilevered falsework later brought the two competitors together again and made them form an autonomous "cantilevered construction falsework company" for the development and operation of a mechanized falsework (Wittfoht 2005, p. 62).

Sixth nucleus: Leonhardt again. The incremental launching completes the period of orientation and competition

Similar to his holistic approach with his Leoba-tendons, Leonhardt put his efforts, together with Andrä and later Göhler (Göhler 1999, pp. 1-9), behind a simple construction method that could manage without high investment costs. It was intended to give smaller contractors a way of building prestressed concrete bridges (Leonhardt 1984, pp. 174-179). To this end, Leonhardt harked back to his predecessors, who had already 100 years before assembled large steel superstructures on land and then pushed them over the piers. Instead of making the falsework movable and concreting the superstructure in its proper place on the bridge, like Finsterwalder and Wittfoht, he finished concreting and prestressing the superstructure in a stationary formwork directly behind an abutment, the so called incremental launching station. With the help of temporary sliding bearings and hydraulic presses he launched half span sections every week unless the superstructure reached his final position. In contrast to Wittfoht's solution, the moving of the superstructure made the construction level decisive for the dimensioning of the incremental launching bridge. This meant a significantly increased need for prestressing steel to avoid oversized cracks, and a focus on short, mono-celled hollow box girders. To prevent the cantilevering moment from becoming to large in the process of movement, a light steel girder was built in at the front, the steel nose (Göhler 1999).

The success of the cantilevered falsework at first made the incremental launching method move into other countries. After a one precursor in segment construction, the *Agerbrücke* in the course of the Autobahn Salzburg-Linz (1959), The bridge across the Rio Caroni in Venezuela (Leonhardt, Baur and Trah 1966) was the first bridge built using the incremental launching method. In 1967 Leonhardt, together with Beton und Monierbau, first used the incremental launching method in Germany in the construction of the 600 m long *Taubertalbrücke* (Wittfoht 1972, p. 253 and Göhler 1999, p. 6). The first incremental launching bridges were partially prestressed, or only reinforced, and were dominated by difficulties connected with the later incorporation of the curved tendons for the final state. In order to keep the centric prestressing in floor and carriageway slab from becoming uneconomical, concessions had to be made in regard to crack control during construction state. Only when Autobahn construction came to an end in western Germany and the patent ran out around 1980 did the incremental launching method catch up with the cantilevered falsework.

Figure 14. The incremental launched Taubertstalbrücke still needed intermediate supports (Wittfoht 1972, Bild 341)

Wittfoht's cantilevered falsework and Leonhardt's incremental launching method were both able to follow the location of the road. However, the optimization of prestressed concrete bridge construction through strict separation of the steps of the process and repeated use of formwork and falsework led to an impoverishment of the language of forms. Identical spans, superstructures with parallel chords, and the concentration on a small number of cross-sections all began to make prestressed concrete bridges interchangeable and left society somewhat irritated.

An insight into the early stressing methods and their critical evaluation is given in the *Allgemeine Runderlaß Straßenbau* No. 5/1953 of the Federal Ministry of Transportation (1953). The state of prestressed concrete bridge construction around 1953 is described by Herberg (1953). Thul (1967) follows the further developments up to the end of the period of completion and competition. Further insights are given by Deinhard (1964) und Wittfoht (1972). For the specific development of the prestressed concrete construction of road bridges in the new states at the time of the GDR, refer to Verch (1998).

THE PERIOD OF COMPLETION (1965 – 1985)

A first finished calculation and design model existed (Mörsch, 1943) by the end of the war. Building on these foundations, which reflected only the single span girder with open cross section, the first German standard DIN 4227 for prestressed concrete was completed, after seven thoroughly discussed drafts, in 1953 still called prestandard. The field of experience finally codified in 1955 was soon left behind in the erection of statically undetermined systems with hollow box cross sections and especially in the discontinuous constructions. The everyday construction experience had overtaken research and development!

A guidance was introduced to check up vibration fatigue of sensitive coupling joints. Also the realization developed, that cracks due to restraining forces can't be helped by prestressing. The amount of reinforcement was raised step by step up to the last edition of the DIN 4227 in 1988 with the aim of preserving durable and robust bridges. The high sensitivity of some prestressing steels against stress corrosion cracking and the incomplete pressure grouting of the internal bounded tendons, are healed through the improved admission for the tendons. A further deficiency was the too optimistically evaluation of strength capacity of the concrete's principal tensile stress. This led to deficits in the shear capacity.

Because of the increasing wealth of experience between 1965 and 1985, the focus of the owners, the departments of transportation, shifted from a purely static optimisation under Feysinnet's verdict on full, threedimensional prestressing towards thoroughly structured and long-lasting bridges, optimizing the crack control through reinforcement and nearly partially prestressing.

While at the beginning of the development stood the superstructure with slender and high main girders, load distributing cross girders and a transversally prestressed carriageway, more and more lying cross sections with a simple longitudinal prestress were developed. The introduction of a quality standard by the owners (Bundesminister für Verkehr 1976) was the quintessential paradigm shift.

At first, the owners could not enforce their views on some important questions of quality control in the standardization commissions. As a reaction, the bridge consultants of the states summed up their quality demands for durable structional design and construction in the supplementary technical conditions of contract of engineering structures. A sufficient concrete cover for tendons and reinforcement was arranged for first in 1980 (Bundesminister für Verkehr 1980, p. 28). Levels of carbonation and chloride contamination measured today confirm this decision which was criticised as intuitive and not cost effective in 1980.

The impetus was the *Blasbachtalbrücke*, built between 1969 and 1970 in the course of the A45, near Wetzlar. The *Blasbachtalbrücke* developed extreme cracks. The conflict between owners and contractors had to be decided in court. The judges, following the written word and not seeking technical explanations for the cracks, demanded the crack and maintenance free structure propagated by the construction companies. After the final verdict of the Higher Administrative Court in Frankfurt in 1980 (OLG Ffm), experts were in shock. But the verdict forced engineers to deal realistically with the maintenance of prestressed concrete bridges and clarify the origin and control of cracks.

In 1979, Friedrich Standfuß's speech (Standfuß 1979) on the future tasks of maintenance and durability of bridges, given on the occasion of the German Concrete Conference, was still greeted with a general shaking of heads. Standfuß illustrated his point in a first documentation of damages on structures in the course of the federal road network (Bundesminister für Verkehr 1984) most due to the ubiquitous use of de-icing salt after the prohibition of tyres with spikes in 1970.

THE PERIOD OF CONSOLIDATION (1985 – 1995)

Between 1985 and 1995, construction and theory of prestressed concrete bridge building are consolidated and its form in everyday construction does not develop further. However, faced with the necessary investments for the maintenance of prestressed concrete constructions from the period of foundation, the owner side gives the impulse to develop construction methods with tendons that can be tested and replaced, facilitating repairs. Metzler and Schmidt showed the way from Dischinger's underspanning to modern external prestressing (1998).

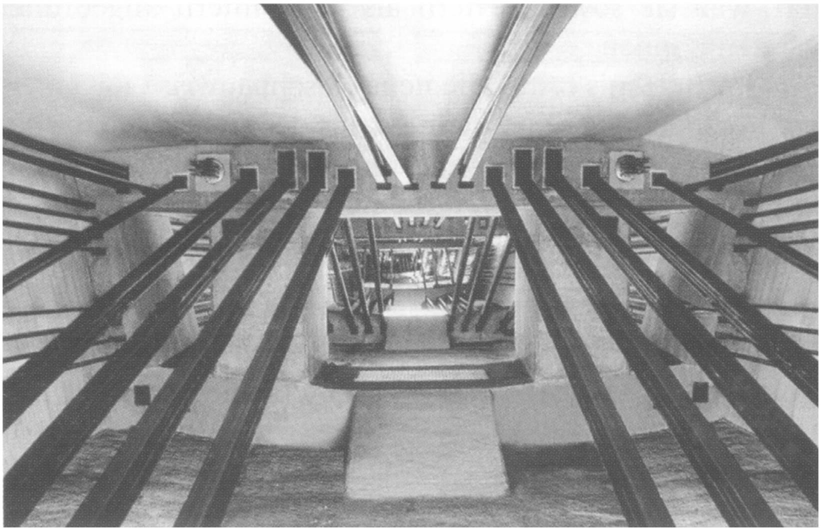

Figure 15. View into the box girder of the Ruhrtalbrücke Rumbeck (1998) with external tendons

THE SECOND PERIOD OF INNOVATION FROM 1995

Jörg Schlaich recollects his souther German forefathers Mörsch and Leonhardt and frees prestressed concrete in form and construction from the narrowness of the beam optimized for construction.

With the year 2000, the advances in concrete technology leave the laboratory and are applied for the first time in pilot projects. The self compacting concrete made for better quality in areas critical to reinforcement. The first high-performance concrete more than doubles the compressive strength of the concrete used in first prestressed bridges. Ultra high-performance concrete reaches the strength of steel. Steel fibres replace the reinforcement and ensure a sufficiently benevolent behaviour even under overload. High density is achieved with fine aggregiate in combination with a very low water-cement ratio. These new concretes, however, create not so much the desire for higher bearing capacity but rather for an increase in durability in particular high capacity of resisting aggressive air and de-icing salt.

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