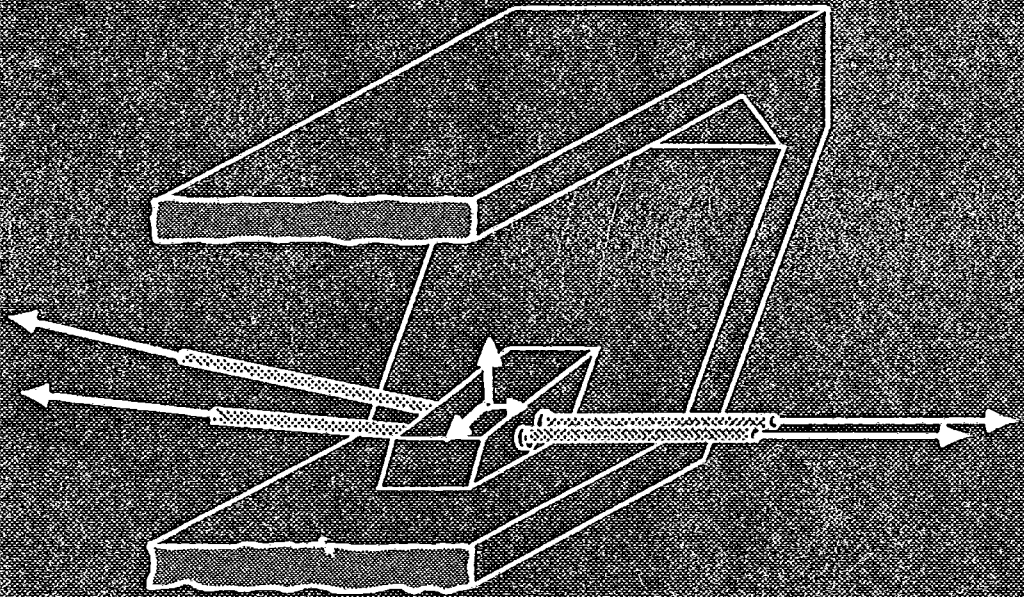


External Prestressing in Bridges



Antoine Naaman
John Breen
Editors

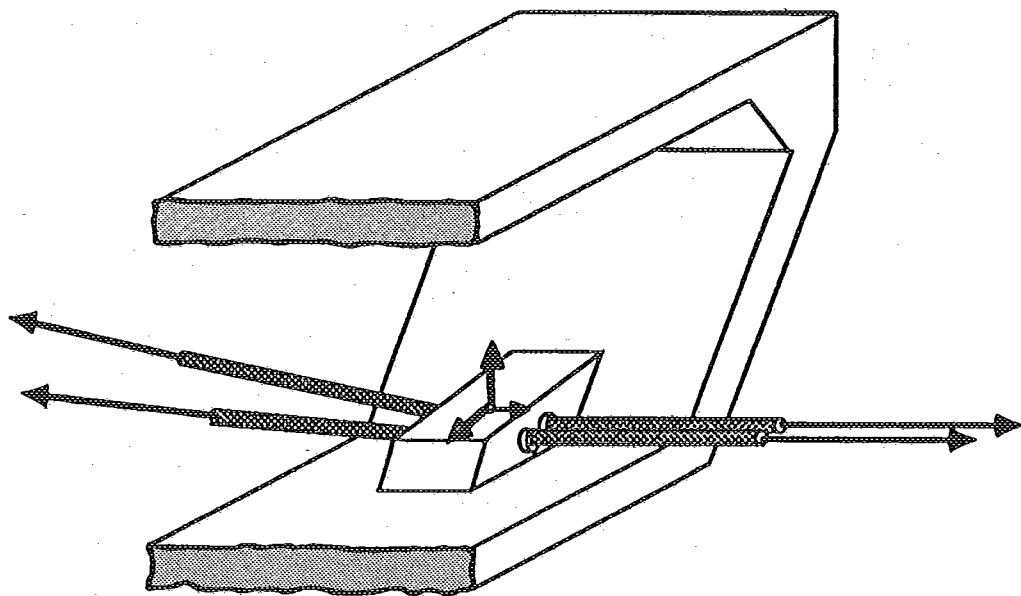


SP-120



Document

External Prestressing in Bridges



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Editors



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PREFACE

External prestressing implies the use of unbonded prestressing tendons outside the concrete section of a structural concrete member. Because of the substantial economic savings and dramatic increase in rapidity of construction possible with this technology, it is being increasingly considered in the construction of new concrete structures, particularly bridges. It is also a primary method for the rehabilitation and strengthening of existing structures.

The decision to organize an International Symposium on External Prestressing in Bridges was initiated by John Breen, Antoine Naaman and Michel Virlogeux during the IABSE symposium on Concrete Structures for the Future, held in Paris in September 1987. The idea was then discussed with Robert Bruce, then Chairman of ACI-ASCE Committee 423, Prestressed Concrete, and Harold Sandberg, then Chairman of ACI-ASCE Committee 343, Concrete Bridges, and received their enthusiastic support. A sponsorship request was then submitted to, and received support from members of Committees 343 and 423. The final approval was given by the Technical Activities Committee of ACI. A steering committee was set forth to take care of detailed organizational and scientific aspects of the symposium. It included the above mentioned main organizers as well as John Scalzi from the National Science Foundation. Co-sponsorship of the symposium included ACI, NSF, PCI, and PTI. The names of the then members of the above mentioned committees and the sponsoring organizations are listed in the following pages.

The symposium took place in Houston, during the ACI 1988 fall convention, and lasted one and a half day; it comprised 18 presentations, about one third of which were from the US and the remaining two thirds from various European countries. Symposium Co-Chairmen were A.E. Naaman and J.E. Breen.

The symposium addressed three main themes: 1) implementation, which includes set up, practical construction aspects, and technologies of construction, 2) analysis and design aspects with particular attention to various strength, serviceability and reliability limit states, and 3) applications, particularly

to bridges. The corresponding papers were assembled into five main sections as shown in the table of contents. Four papers that could not be presented during the symposium are included in the proceedings.

Two state of the art reports on external prestressing, one by M. Virlogeux and the other by A.S.G. Bruggeling are presented in this volume. A brief historical review can be found in these reports. In addition, a discussion with Kent Preston revealed an additional historical milestone, namely, that the John A. Roebling and Sons Corporation developed the idea of external tendons and tested a one tenth scale model of 200 ft. (61 m) simple span bridge in its laboratories in the late forties. The company expected to use the system on the first US prestressed concrete bridge, the Walnut Lane Bridge in Philadelphia. However, the Philadelphia city engineer decided to go with a design by Magnel which included standard posttensioning. In 1952, the Cuban Government, under the direction of Luis Saenz, requested the technical assistance of Roebling; their cooperation led to the construction of the Canas River Bridge in Cuba, which can be claimed as the first American application of external prestressing in bridges. Kent Preston, Mario Suarez and Ignacio Martin were involved in design, construction, and supervision of the bridge. It consisted of hollow cored box girders, prestressed with one inch diameter external galvanized steel strands placed inside the opening of the box. At diaphragms, the tendons were held in position by cast iron saddles. The bridge, which is still in operation, has three continuous spans, with a center span of 249 ft. (76 m) and two 50 ft. (15 m) end spans. The bridge was completed in December 1952. Three other bridges using the same concept were built thereafter in Cuba. A detailed description of the construction of the Canas River Bridge can be found in an article by Kent Preston in the December 27 1956, issue of Engineering News Record.

External prestressing has evolved dramatically and with it many challenges were encountered and problems resolved. A great deal has been achieved so far as is evident from the papers of this volume.

The editors, the members of the steering committee, and the members of ACI-ASCE Joint Committees 343 and 423 wish to thank all authors and presenters who have contributed to the technical sessions and to this volume, and all reviewers of the original papers for their suggestions and comments. Thanks are also

due to the National Science Foundation for bearing part of the travel expenses of overseas speakers, to the staff of ACI who helped organize the symposium and prepare this publication, and to PCI and PTI for co-sponsoring the symposium. We hope that the reader will find in this volume the comprehensive state of knowledge it aims to offer.

August 1989

Antoine E. Naaman
John E. Breen

Editors

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External Prestressing: from Construction History to Modern Technique and Technology

by M.P. Virlogeux

Synopsis: The development of external prestressing has been one of the major trends in construction during the last ten years, along with the development of concrete cable-stayed bridges and with the increasing use of high strength concrete. But external prestressing has been used in the early ages of prestressing, in Germany with Franz Dischinger and Ulrich Finsterwalder, in Belgium with Magnel, and in France with Henri Lossier and Coignet. The idea came back in the United States with Jean Muller, and in France under the influence of SETRA. After a historical review, the main principles of the design of externally prestressed bridges are presented. The paper then details the influence of the construction method on the external tendon organization: bridges built span by span, bridges built by the cantilever method or by methods which are mechanically equivalent, and bridges built by the incremental launching method. Some practical problems are finally evoked, such as handling heavy jacks. A last chapter is devoted to composite structures, with concrete top and bottom slabs and with steel webs, prestressed by external tendons. The French experimental constructions of this type did not appear economically interesting, and prestressing classical composite structures is not yet considered as a good solution for the same reason. But external prestressing is now widely developed for concrete bridges in the United States, in France, and more recently in Belgium, in Switzerland, in Venezuela, in Germany and in Czechoslovakia.

Keywords: box beams; bridges (structures); cable-supported structures; cantilever bridges; composite construction (concrete and steel); concrete construction; history; prestressed concrete; prestressing; prestressing steels; reviews; segmental construction; structural design; unbonded prestressing

Michel P. Virlogeux is graduated from Ecole Polytechnique and from Ecole Nationale des Ponts et Chaussées. He is Docteur Ingénieur from Paris University. He is Chief Engineer in the French Ministry of Transport, and head of the Large Bridges Division of SETRA (Bagneux). He was the first recipient of the IABSE Prize, in 1983. He is a part-time Professor at the Ecole Nationale des Ponts et Chaussées.

INTRODUCTION

In the past ten years, numerous prestressed concrete bridges have been built in the United States of America and in France with external tendons, that is with tendons outside the concrete. More recently, this solution has been used in Belgium and in Venezuela, and will be used in Switzerland and in Germany.

The idea is not new. Several bridges were built in this way in the early days of prestressing, namely: 1) in Germany first, with the bridge at Aue in 1936 [5]. Designed by Franz Dischinger, the bridge, built before the wide development of prestressing steel, is prestressed by bars of high strength steel, the yield stress of which is about 500 MPa. 2) In Belgium then, under the influence of Magnel, with the Sclayn bridge in 1950 [8, 9]. And 3) in France between 1950 and 1952; the bridge at Villeneuve-Saint-Georges, designed by Lossier; the bridges at Vaux-sur-Seine and Port à Binson, built by Coignet; and the bridge at Can Bia. In these projects, external prestressing was developed to by-pass Freyssinet's patents on prestressing systems.

These first attempts did not produce excellent results: most of these externally prestressed structures suffered from corrosion.

Smoke from steam locomotives corroded the external prestressing bars of the bridge of Aue, which had to be cleaned and painted. It also required retensioning twice, in 1962 and 1980, to restore the losses caused by steel relaxation and concrete shrinkage and creep, too important for the low steel capacity [13, 14, 51].

For the construction of the Villeneuve-Saint-Georges bridge [12], Henri Lossier used large monostrands – similar to those used for suspension bridges – which were left bare in the box-girder, with a single coat of bitumen paint (figure 1). But Lossier had foreseen the need to make possible the external tendons replacement. This made it possible to replace one cable rusted by water running through an inspection chamber in the top slab. Due to an excellent maintenance, the bridge has not suffered other problems. But the deviations of the external tendons were enforced by very sophisticated and expensive struts in reinforced concrete or steel, which dissuaded engineers from further investigations in this field (figures 2, 3).

The arrangements of the other French structures were more economical, with simple concrete cross-beams for the external tendons deviations. The external tendons were made of small diameter parallel prestressing wires (5 to 7 mm).

In Port à Binson bridge, protection of the external tendons by a bitumen paint proved to be sufficient (figures 4, 5). It would have been in Vaux-sur-Seine bridge, too, if birds had not nested in the bridge, depositing acid droppings on the external tendons which thus suffered from corrosion (and from insufficient maintenance); the bridge had to be strengthened recently with additional external tendons [10, 11]. For the construction history, the tendons were placed and anchored at the abutments, and then only tensioned, by transverse deviations; at some selected points, the tendons were parted by jacks, and these deviations maintained by concreting deviation blocks; at

some other selected points, the tendons were drawn together by jacks, and these deviations maintained by steel braces (figure 6).

On the other hand, the poor design of the Can Bia bridge, with anchorages in the top slab, allowed water to flow along the external tendons which were never repainted after construction, causing major corrosion and rupture of wires making it necessary to close the bridge to traffic some years ago and consider its demolition (figures 7, 8).

This experience gave a poor image of external prestressing, and very few externally prestressed concrete bridges were built in the sixties and in the seventies except for a series of road bridges in Belgium, between 1960 and 1970 ; and in England the Bournemouth bridge [15], and the Exe and Exminster viaducts [17]. Few of these constructions were a success.

The Belgian road bridges were built with external tendons embedded in a cylinder of concrete ; in some bridges, the concrete cracked and the tendons were corroded. These corroded tendons have been recently replaced.

In the Bournemouth bridge, the external tendons were large monostrands, as for Villeneuve-Saint-Georges bridge. But they corroded and had to be replaced some years after construction.

We must note that all these problems concerned prestressing steel corrosion and not poor mechanical behaviour of these bridges – due, for example, to the lack of bond between concrete and tendons. They always performed adequately from the structural point of view, even the Can Bia bridge despite the rupture of about 10 to 15% of prestressing wires.

The recent return to external prestressing, under the influence of French engineers – Jean Muller in the United States, and SETRA in France –, has been made possible by the development of the prestressing technology. The development of high-capacity tendons (12, then 19 strands of 15 millimeters and more) has resulted in a reduction in the number of external tendons which eases design and construction. And, above all, the experience of strengthening some classical prestressed concrete bridges, in which the initial prestressing forces were not great enough, has made it possible to put into use protective systems adapted to ensure resistance to corrosion of external tendons.

Furthermore, experience in strengthening these bridges, which perforce had to be by tendons outside the concrete, made designers aware of the advantages of external prestressing. This led them to consider its use in building new bridges. The principal advantages are the considerable simplification of the lay-out of the tendons and the large reduction in losses of prestress due to friction.

The need to allow for the replacement of the stays during the construction of the footbridges at Meylan and Illhof led to the idea that external tendons could be replaced, not knowing at the time that this had been foreseen by Henri Lossier, 30 years before.

Finally, some traditionally prestressed bridges were built by incremental launching with the help of some temporary external tendons – to increase central prestress during launching without increasing the cross-section weight (bridges at Aiguilly [69.2], Bléré [45, 69.2], and more recently Kouilou [44]). And, in the Sathorn bridge, in Thailand, temporary tendons – partly inside the concrete, and partly outside the concrete above the top slab – were placed with a lay-out in opposition to the classical undulated tendons inside the concrete, so as to balance the moment created by internal tendons and produce a central prestress during launching [41].

All these ideas helped the development of external prestressing to the point it is today, in the United States and in France.

To understand the difference in design of externally prestressed bridges in these two countries, one must know the real objectives of this development in each of them.

In the United States, the primary objective is to reduce the construction cost, because contracts are almost always given to the lowest bids. External prestressing has then been a way to reducing the structures weight, mainly by reducing the webs thickness. And the prestressing technology is the simplest possible, the most economical, without considering external tendons replacement. In these conditions, Figg and Muller has been able to build a series of segmental bridges, competing with success against standard AASHTO beams.

The situation is completely different in France. External prestressing, developed under the influence of the Government, is first a way to improve construction quality. External prestressing leads to simple tendon lay-out, with very small construction deviations ; reduces friction losses ; improves the concreting conditions by eliminating ducts from the webs; improves the grouting conditions; and, above all for clients, external prestressing allows for external tendons replacement, and for an easy strengthening of structures. But the prestressing technology cannot be the same as in the United States and is more expensive, reducing largely the economical advantages of external prestressing.

External prestressing is now widely utilized in France, and practically all large bridges are now built with external tendons ; even when the contract comes from an alternative design. This proves that there is still an economical advantage when tendons replacement is an obligation.

Recently, some bridges have been built with external tendons in Belgium, with designs from René Greisch and Bruno Cremer (Ben Ahin and Wandre bridges), and in Venezuela, with a Figg and Muller design [68]. The interest in external prestressing is developing in Switzerland, in Germany and in Czechoslovakia.

DESIGN OF EXTERNALLY PRESTRESSED CONCRETE BRIDGES

General Consideration of the Design of the Tendon Lay-out

Tendons external to the concrete pose problems of how to spread the forces to the anchorages and of local bending at the anchorages, which are much greater than with traditional tendons, since the forces no longer go towards the concrete mass of the structure. In particular, it is much more difficult to anchor external tendons to isolated bosses than to anchor internal tendons to them. The anchorage force creates major shear forces at the junction between the boss and the concrete panels, as well as introducing bending which cannot be ignored (figure 9). Logic thus led designers to anchor external tendons to massive elements and thus, from preference, to the existing members – bracings on piers.

The simplest cable system thus consists of the use of tendons in each bay, anchored to the cross-beams on the piers, and crossing within these cross-beams. Almost all structures have been built in accordance with this principle, adopted for the first time for the Long Key bridge (figures 10, 11) [19, 20, 21, 29].

Clearly, for external tendons to have the best lay-out so far as bending and shear are involved, they must be deviated in the span so as to be at the bottom fibres in the key zone. This deviation has been arranged, in the classic box sections, sometimes by small deviation blocks at the junction of the lower slab and the web, and sometimes by cross-beams.

The solution using deviation blocks has been used for numerous bridges : all the American bridges of Jean Muller, and the viaducts of Vallon des Fleurs and la Banquière, built in France just before we developed our action in this field [50, 69.1]. It enables the tendons to be deviated one by one, selecting the anchorage point for the different tendons in the cross-beams on the piers in such a way that the deviation force is introduced without bending – so far as possible – in the web and the lower slab. The lay-out of the tendons can then be in line with the force diagrams, leading to very light structures. But, as every tendon can only be thus deviated near to the web, it is necessary to get those tendons which have already been deviated away from the web, resulting in a non-linear lay-out in plan (figure 11).

This led us to a preference for deviating the tendons by means of special cross-beams – lighter than the cross-beams on the piers –, seeking simple lay-outs, each tendon being placed in a vertical plane (or slightly inclined) with occasional slight alterations at the anchorages. It is then preferable to give the same lay-out in elevation to all the tendons, to reduce the angular deviations. The choice of thickness of the web is linked to the number of cross-beams : if there are only two deviation cross-beams per bay, it is not possible to have a perfect lay-out for shear and it is necessary to have relatively thick webs ; on the other hand, if one accepts four deviation cross-beams per bay, this results in extremely thin webs if the cross-beams are properly placed and the cables at the right levels. The extreme case is that of the bridge at La Flèche, where the extremely reduced height of the box called for the placing of numerous deviation cross-beams to limit the web thickness (figures 14 to 17) [27, 39, 69.2]. Almost all the bridges in France with external tendons have been built in accordance with these principles.

But the situation is rather different for box-girders of constant height, than for box-girders of variable height.

The first bridges which had been built were of constant height. With two deviation cross-beams in each bay, the cross-beams must be placed not far from the third points of the span to fit with bending conditions. The ideal design for shear forces is, of course, with tendons radiating from the cross-beams on the piers, which progressively reduce the shear forces produced by the structure weight and loads ; as is done in the Figg and Muller designs, which are equivalent from a shear forces point of view to designs using a series of deviation cross-beams in the spans (figure 18).

The situation is very different with beams where the height is parabolically variable. Due to the height variation, the deviation cross-beams – if there are two in each bay – must be very close to the key zone. But the shear force reduction is then very small, unless the box-girder height is very important in the key section, as it is for the bridge near Chinon (figure 22) which had been designed for very heavy nuclear transports (650 metric tons) [45] or for the Ré Island bridge. If the key section height is small, it is necessary to improve the shear forces design by adding some deviation cross-beams. There is no need for an important shear force reduction near the piers, due to the rapid height variation, and it is favourable to increase the tendons inclination in the intermediate parts of the bay. But the best solution is a modification of the height variation, with the two ends of the bay having a parabolically varying height, each of them about 20 to 25% of the span length, and with a central part of the bay of constant height, evidently greater than at the key section with a classical height variation (figure 19). The bridge at La Flèche and the Pont à Mousson viaduct (figures 20,21)

[37, 69.2] were designed like this for aesthetic purpose, before we understood the advantages of this solution.

Finally, with the construction of the viaduct at Pont à Mousson on the river Moselle, we extended external tendons over two bays, to reduce the number of anchorages in the cross-beams on the piers, to limit the forces to be spread in the cross-beams and from there into the cross-section ; and also to limit the geometric congestion due to a great number of anchorages. This resulted in an economical advantage since the cost of the anchorages is important for replaceable external tendons.

General Consideration of Construction Problems

The problem of the construction method then arises.

If the bridge is built bay by bay, and if it is desired to place all the tendons outside the concrete with anchorages in the cross-beams on the piers, it is necessary to do without the prestressing forces during the construction and to provide something else to support the weight of concrete during construction. Numerous solutions have been employed :

- building the whole deck on centering, or bay by bay on centering ;
- building on temporary supports with the help of temporary prestressing bars ;
- using removable centering ;
- using temporary stays...

Concerning bridges built by the cantilever method, we developed the idea of a mixed prestressing system, with some tendons within the concrete, their number being strictly limited to that required for construction, to balance the cantilevers self-weights. External tendons are only installed – from on-pier section to on-pier section – after completion of the final key section.

External prestressing has been applied only recently to incrementally launched bridges, and several solutions have been put forward.

Bridges built Bay by Bay

The simplest case is where a bridge is built bay by bay, one at a time or in groups of bays, or the whole deck in one single operation. In all cases the method of construction must make it possible to balance the forces due to self-weights of the span (or of the spans) without using its final prestress, which can only be placed and tensioned when the construction of the bay (or of the bays) is complete. At which time all tendons can be placed outside the concrete and can be anchored in the cross-beams on the piers.

Following is a list of the different methods developed for the construction of bridges bay by bay, or in groups of bays, according to this principle :

- bridges built in one single operation on general centering or scaffoldings : Martinville viaduct, also called Lyons viaduct [45, 69.2], and Serignan bridge over the river l'Algues [45], in France; the scaffoldings support the concrete weight during construction ;
- bridges built bay by bay on scaffoldings ; the scaffoldings support the weight of the built bay ; they are dismantled when the bay has been prestressed, and installed for

- the construction of a new bay ; for example, the small spans of the Pont à Mousson viaduct (figures 20, 21) [37, 69.2], and the viaducts of the second line of the Lille Mass Transit System (VAL), in France; note that a great part of the tendons are internal in the small spans of the Pont à Mousson viaduct, though they could have been all external;
- bridges built bay by bay with the help of a moveable erecting beam on which the precast segments of the span to build are installed ; this is the method used for the greater part of the American bridges designed by Jean Muller : Long Key, Channel Five and Niles Channel bridges (figures 10, 11) [19, 20, 21, 29], Dauphin Island bridge access spans, Wiscasset bridge, and the two viaducts for the Mass Transit System in Atlanta [32], to mention the first ones ;
 - in the same way, bridges built span by span on a moveable centering system, on which each bay could be concreted ;
 - bridges built span by span with the help of a launching beam ; this could be imagined for cast in situ bridges, each bay being concreted on the beam in the adapted position ; but this solution has been used with precast segments : for the Seven Mile bridge, and for the access spans of the Sunshine Skyway bridge; and for the Bubiyan bridge in Koweit designed and built by Bouygues [24, 25, 30] ; in this last case, the launching beam was used like a gigantic crane suspending all the segments of the span to build (figures 12, 13); the latest application, with a very classical launching beam, is the construction of four viaducts for the Romulo Bettancourt highway, in Venezuela, designed by Jean Müller [68];
 - bridges built span by span with the help of a temporary cable-staying designed by Camperon Bernard : the Vallon des Fleurs and La Banquière [50, 69.1], viaducts near Nice, and, recently, the Frébuge viaduct and the Francin bridge, all of them in France ;
 - and finally, bridges built span by span with the help of multiple temporary supports and of prestressing bars, with the example of the viaduct in Saint Agnant, between Rochefort and La Rochelle, in France [35, 69.2].

These methods are mainly adapted to very long bridges, what explains that they have been much more developed in the United States than in France.

Bridges built by the Cantilever Method

The principle of the mixed cabling relies on balancing, with the fewest tendons possible, forces due to the cantilever self-weights (and to the carriages weight) by tendons within the concrete, segment after segment, with a lay-out which is not far from the lay-out of classical cantilever tendons. But these cantilever tendons remain horizontal and are situated and anchored in the upper nodes, at the junctions between the webs and the top slab.

This makes it possible to build the successive cantilevers, and to place the external tendons – from on-pier section to on-pier section in one bay – just after closing the span, for the typical intermediate spans.

Many bridges have been built this way in France : the main spans of the Pont à Mousson viaduct (figures 20, 21) [37, 69.2] ; the bridges near Toul, near Rumilly [45, 69.2] and near Chinon (figure 22) [45] ; the main spans of the Roquebillère viaduct near Cahors (figures 30 to 34), and of the Poncin viaduct on the A 40 highway (figure 35 to 40); more recently the Arrêt Darré viaduct near Tarbes (figure 23, 24, 25), the Persan-Beaumont bridge over the river Oise, and the Ré Island bridge which is the largest construction of this type. This method is currently being used for the Champ du Comte viaduct near Chambéry and the Cheviré bridge near Nantes, which will be of the same importance as the Ré Island bridge ; both are under construction.

Some of these bridges are wide, with box-girders about 20 meter wide, such as the Poncin and Arrêt Darré viaducts, and the Cheviré bridge. The webs are about 50 to 60 centimeter thick, which is not much as compared to the cross-section.

Jacques Mathivat –working for the contractor on the SETRA design of the Cheviré bridge – decided to utilize some of the cantilever internal tendons in the webs to increase the shear force reduction. Due to the web thickness, this in no way worsened the concreting conditions. After finalization, this idea led to a very nice shear-forces distribution.

Of course, these ideas are also used for bridges built by methods which are producing the same force distribution as the cantilever method. At first for bridges built from the two sides by the incremental launching method, such as the Cergy Pontoise bridge, over the river Oise, near Paris [45, 69.2]; the Amougueux bridge in Morocco, built by Spie-Batignolles; and the bridges for the G12 highway interchange, near Paris. But also for bridges placed by rotation, such as for the bridge over the river Loir at La Flèche [27, 39, 69.2], which is the first bridge built with a mixed prestressing system, and which must be considered as the prototype of this solution, such as the Long Key bridge is for bridges built bay by bay (figures 14 to 17).

In all cases, analysis has shown the need for some internal continuity tendons (from one to three or four tendons per web), to avoid too high a requirement for the external prestress, excessive over the piers because of the presence of the internal tendons. These few internal tendons help for immediately closing the spans, providing the necessary strength capacity, because short internal tendons can be placed and tensioned much quicker than long external tendons.

Some other ideas have been developed for the external tendon lay-out in bridges built by the cantilever method.

At first, Bouygues and Philippe Lecroq decided to reproduce a traditional tendon lay-out for the Sermenaz viaduct, over the river Rhône near Lyon, with cantilever tendons and continuity tendons, all external, and with anchorages distributed in the spans, placed in vertical anchorage ribs (figure 26) [36]. But, in the end, the multiplicity and weight of these anchorage ribs outbalanced the webs lightening, and this solution has not been reproduced.

On an other hand, Jacques Fauchart considered the excess of prestressing forces in the pier zones of our designs, and managed to double the number of external tendons in the key zones by anchoring them in deviation cross-beams in the spans, with an overlap of tendons in the key zones. In such a situation, external tendons only pass through the cross-beams on the piers, without anchorage there (figure 27). The Darse du Gaz de France viaduct at Alfortville, on the A 86 highway near Paris, was built like this [43, 69.2]. With this design, however, the shear force reduction is only half as much, and the deviation cross-beams are more numerous and heavier ; which results in somewhat heavier structures (figure 28).

This idea has been partly used by Jacques Combault for the Très Cassés bridge, over the river Garonne, near Montauban. Some external tendons are anchored in the cross-beams on the piers and some in the cross-beams in the spans. But this results in a very complicated geometry and in an increase of reinforcement. A somewhat similar situation can be found with the Venant viaduct, on the A 71 highway.

As a conclusion, despite the necessity of a greater quantity of prestressing steel, the simplest solution appears the best.

Finally, we cite the Sylans and Glacières viaducts on the A 40 highway, built by Bouygues according to Pierre Richard's ideas [59, 63]. As for the Bubiyan bridge, the structure is a prestressed concrete spatial truss, this time built by the cantilever method. The tendon arrangement is rather complex, with :

- temporary, straight cantilever tendons, external ;
- few final straight cantilever tendons, internal ;
- final, undulating cantilever tendons, external ;
- some additional, undulating external tendons, placed after construction of the cantilevers ;
- and some additional internal tendons, straight, placed in the nodes to the SETRA demand to improve the ultimate behaviour.

This looks a bit sophisticated, but an excellent distribution of prestressing forces is necessary in such bridges, due to the relatively reduced shear force capacity of triangulated structures.

Incremental Launching

The most recent developments in the field of external prestressing concern bridges built by the incremental launching method.

The first solution proposed was based on the idea of mixed cabling ; launching tendons within the concrete, horizontal and placed in the upper and lower nodes – at the junctions between the webs and the slabs – and external, undulating tendons placed after launching and anchored in the cross-beams on the piers (figure 29). As compared to traditional internal tendon lay-out – where the launching tendons are placed in the upper and lower slabs, to free the webs for the internal, undulating tendons, placed after launching –, this solution allows for lightening both the slabs and the webs. What results is a fantastic economy in weight. This idea was put forward for several projects : the basic scheme for the Jules Verne viaduct at Amiens, and tenders from Spie-Batignolles for the lake Mosja bridge in Norway and for the Bléré bridge over the river Cher in France. But it has only been used, in this simplified form, for the access spans of the Roquebillière viaduct, near Cahors, which had been launched with a temporary support in each span (figures 30 to 34).

This solution has been improved by Claude Servant, who added some temporary launching tendons outside the concrete, these being straight, to reduce the number of the internal, final launching tendons, which are also straight. Of course, the final, undulating external tendons are placed only after launching. This solution has been used for the construction of the access spans of the Poncin viaduct, over the river Ain, also launched with a temporary support in each span (figure 35 to 40).

Of course, in both cases the internal horizontal launching tendons could be divided in segments according to the division of the beam in successive segments, cast on the prefabrication bed on one bank. This made it possible to detension and remove some of these tendons, in the Roquebillière viaduct, in the zones where they are unfavourable for flexural forces after launching. This was not necessary in the Poncin viaduct, due to the existence of temporary external tendons, but some straight tendons have been placed and tensioned after launching in the favourable zones: upper nodes in the pier zones, lower nodes in the spans.

Another family of solutions derives from an idea developed for the construction of the Sathorn bridge, in Bangkok [41]. The internal tendons were placed during

construction with a lay-out as for a bridge cast on centering, passing in the upper part of the webs on the piers, and in the lower part at mid-span. To result in a central prestress during launching, the moment which they created had to be balanced by placing temporary tendons in opposition. These temporary tendons passed also in the webs, but they were placed above the deck in the zones of positive moment in final position.

The basic idea consists of balancing the prestressing moment due to final tendons, having a classical lay-out and tensioned before launching, by temporary compensating tendons, so as to obtain a central prestress during launching (figure 41). This idea can be applied whether the final tendons are inside or outside the concrete, and, of course, the temporary compensating tendons must be external.

The idea was adopted by Michel Placidi for the construction of bridge numero 33 on the Autoroute du Littoral at Marseilles by placing during construction the final, undulating internal tendons in the webs, balanced by temporary external, undulating and compensating tendons. Some horizontal final tendons were also placed inside the concrete – tensioned segment by segment on the prefabrication bed –, and some additional external, horizontal temporary tendons were placed in the forward bay. Once the structure was in place and the compensating tendons had been stripped, external undulating tendons completed the prestress (figure 42, 43, 44).

The idea was simplified and improved by Jacques Combault for the construction of the viaduct over the river Durance, the Val de Durance viaduct [57, 61], with all tendons external. One part of the tendons, final and undulating, was placed during construction, balanced by temporary compensating tendons, also external; some temporary horizontal, external tendons completed the prestress during launching. After launching, the temporary tendons – horizontal and compensating – were removed and the final external prestress was completed. We must note that the bridge was launched with a temporary support in each span, only used for the passage of the front-bay (figure 45).

Jacques Combault finalized this solution with the construction of the Amiens viaduct, almost one kilometre long [57, 61]. Some of the final external tendons, tensioned at the construction on the prefabrication bed, are horizontal, not far from the top slab (figure 46).

This solution is extremely efficient, because of the large compression stresses during launching, due to the addition of final and compensating tendons. This gives a high shear capacity to the box-girder, allowing very thin webs : 30 centimetres for the Amiens viaduct, with spans more than 50 meter long ; compared to the 50 to 60 centimetres that we had ten years ago in the same situation.

But, personally, we have a preference for keeping some horizontal tendons inside concrete, in the nodes, as done by Claude Servant for the Charix viaduct, launched with spans 64 meter long [66], because nodes constitute a very good place for some internal tendons, and because keeping some internal tendons limits the geometric congestion of external tendons in the box-girder and improves the bridge ultimate behaviour (figure 47).

To these new ideas we have added, with Michel Placidi, the re-use of temporary tendons as final prestressing tendons. For the bridge numero 33 in Marseilles, which has two parallel decks, the temporary tendons for the first deck were re-used as temporary tendons for the second. Even though they were not used in Marseilles, specifications were laid down for their re-use as final tendons, and some technological dispositions and operations were later invented to make this re-use possible and easy. But the increasing competitiveness of composite bridges has not yet provided the occasion to put them into practice.

In fact, the last bridge incrementally launched in France was the viaduct on the river Sîoule, on the A71 highway. But we cannot consider its tendon arrangement as a progress as compared to those of the Val de Durance viaduct, the Amiens viaduct or the Charix viaduct.

We have to wait until next year, for the beginning of the construction of the access spans of the Normandy bridge, to see what we now consider as the finalized solution, with:

- internal horizontal tendons, in the upper and lower nodes, placed and tensioned during construction;
- a limited number of final undulated tendons, placed and tensioned during construction;
- and the adequate number of temporary antagonist undulated tendons, detensioned after launching and re-used one after another, in the same web, as final tendons.

Handling and Placing Jacks

The jacks used for tensioning external tendons of high capacity (19 strands of 15 millimetres and more) are extremely heavy, from 800 kilograms to more than one metric ton.

In the span-by-span construction, this led designers to place active anchorages on the front pier of the progressing construction, where the access is free to the on-pier cross-beam before placing (or concreting) the segments of the next span; and to place passive anchorages on the rear on-pier segment, on the last but one pier. This makes it possible to handle heavy jacks with small mobile cranes from outside, which is not possible in the box-girder on the rear on-pier segment. This solution has been systematically used by Jean Muller in all his bridges, and re-used as often as possible, for instance for the Saint-Agnant viaduct. It was slightly adapted for the Bubiyan bridge, in which the cables were coupled, on the rear on-pier segment, to those of the previous span, and tensioned from a small mobile carriage in front of the progressing construction on the front pier.

For small three-span bridges built in a single operation (such as the Martinville and Sérignan bridges), or so built that all external tendons could be tensioned in a single operation (such as the La Flèche and Cergy-Pontoise bridges), the normal situation consists in placing external tendons from one abutment to the other, anchored on the extreme cross-beams. Thus jacks can be handled from the outside, with small cranes. However, fewer tendons are usually necessary in the side spans than in the main one; for the Chinon bridge, Grands Travaux de Marseille imagined to place tendons on two spans only, symmetrically, in such a way that their number is double in the central span (with other longer external tendons, from one abutment to the other); but they placed passive anchorages on the intermediate supports, to keep all active anchorages at the abutments and prevent handling problems.

The construction of the Pont à Mousson viaduct evidenced that handling and placing heavy jacks inside a box-girder was not easy, due to their weight, due to the existence of the deviation and on-pier cross-beams, which makes the transport of jacks difficult, and due to the small distance between anchorages and top slab (figures 48, 49). For later applications, the designers had to organize the tendon layout in such a way that the distance between anchorages and top slab could be increased; and the prestressing system suppliers had to devise methods for handling and placing heavy jacks inside the box girder when necessary, for all long bridges built by the cantilever or the incremental launching methods.

Spie-Batignolles for LH system (figure 50), VSL and Freyssinet designed separately a mobile handling equipment, able to place the jack in an upper corner of the box girder; and SETRA designed, for the Ré Island bridge, a permanent rail, from which the tensioning jack could be suspended and moved along the bridge, to the on-pier anchorages (figures 51, 52).

But this problem also led to a purely technological solution: to eliminate the problem raised by handling and placing heavy jacks, Freyssinet imagined to tension the external tendons strand by strand, with a very light jack which can be moved by workers without any equipment (its weight is about 30 kilos). The idea has been to create bunches of coated-greased strands. But in the deviations the pressure produced by the external layers cut the coat of the internal strands. Freyssinet then imagined to place the coated strands in a continuous high density polyethylene duct (HDPE), injected with cement grout before tensioning the strands. There technology meets design.

Some last Remarks on Dimensioning

This presentation of a great number of examples evidences important differences in dimensioning. They mainly come from the Code-specifications: the live loads from the American Code are much lighter than those in the French one, what leads to much lighter structures. But the differences also come from the construction philosophy and organization.

The French Bridges Administration prefers designing rather comfortable structures, for easing construction and increasing durability. For this reason we do not take all possible advantages from external prestressing, and, for example, we do not design webs as thin as they could be. We can, in the French system, specify for each bridge a lower limit of the web thickness.

We also try to limit shear forces in the service limit state conditions, and to balance the greatest possible part of the bending moments due to permanent loads by antagonist prestressing moments, as recommended by Renaud Favre for example. Because deformations, cracks and durability are practically only conditioned by the situation in the structure produced by permanent loads, dead loads and prestressing forces.

This leads to a rather great number of undulating tendons, greater than it could be to only stick to Code-specifications. In the case of bridges built by the incremental launching method, it could be more economic to increase the number of final straight tendons – internal or external – than we do, because it would limit the number of temporary antagonist tendons and thus tendon handling. But the final distribution of stresses, under permanent loads, would not be so favourable.

We can evaluate the distribution of permanent forces in bridges of constant height with a classical organization of tendons:

- tendons all external and undulating, each of them flying on one span from pier to pier (or on two spans);
- or some external and undulating tendons, with in addition continuous straight tendons - internal or external -, flying on one complete span, or on several spans.

For long highly hyperstatic bridges with regular spans, the effect of straight tendons is a centered prestress, whatever their precise position is. And we can assimilate the bending effect of the undulating external tendons to a lifting uniform density of forces, given by:

$$P_{\text{prec}} = \frac{8 F_{\text{und}} \Delta e}{L^2}$$

where F_{und} is the prestressing force produced by undulating tendons, Δe the undulation total amplitude, and where the span is noted L . This estimate is the most precise as the external tendon layout is closer to a parabola (figure 23).

This lifting action of the undulating tendons balances a part of the dead loads, the uniform density of which is noted P_{dead} . The ratio $\left(\frac{P_{\text{prec}}}{P_{\text{dead}}}\right)$ is a good indicator of the stress distribution under permanent loads. We try to balance this way at least 60 to 70 per cent of the permanent loads, and we reach an extremely good situation with a ratio between 0,70 and 0,80. We hope to have from there the best conditions for a good durability of the externally prestressed structures.

This approach is not in disagreement - to our opinion - with the philosophy of partial prestressing for cast-in-situ bridges; because such a situation under permanent loads leads to some residual compression under frequent loads, and avoids any fatigue problem; and because there is no contradiction with limited tension under extreme live loads. Even if these tensions perhaps seem too limited to some colleagues.

PRESTRESSING COMPOSITE BRIDGES

In their search for lightening structures, French engineers have invented the substitution of much lighter steel webs for the concrete webs of classical box-girders. The pioneer in this field is Pierre Thivans, from Campenon Bernard, who developed the idea of a box-girder made of steel folded webs and concrete slabs.

Of course, these structures have to be prestressed so that the concrete slabs – top slab and bottom slab – are subjected to compressive stresses under the effect of permanent and frequent loads.

The prestressing tendons can be within the concrete of the slabs – in the bottom slab at least in the central part of the spans, and in the top slab at least near the piers. But the prestressing tendons can be also outside the concrete. Due to the development of external prestressing in France, this second solution has been immediately adopted for the first applications, with these advantages:

- a mechanical continuity of prestressing forces ;
- an excellent distribution of forces, for bending forces as well as for shear forces;
- and a shear force reduction, leading to some possible economy in the web thickness and the connection.

The prestress design of these bridges follows the same principles as for prestressed concrete bridges, presented above.

But these ideas were coming from designers normally interested in prestressed concrete bridges, who simply introduced steel webs in their usual way of thinking. On the other side, some designers normally interested in steel construction – at least partially – had already thought of prestressing traditional composite bridges.

This results in the two directions that we shall cite.

Four small bridges have been built these last years in France, following the ideas initiated by Pierre Thivans. We shall not present them in the chronological order, but in the logical order, from the simpler to the most sophisticated.

Fougerolle has built a small bridge, which is an isostatic span over the A 71 highway near La Ferté Saint Aubin, not far from Salbris [11.5]. The box-girder is made of two concrete slabs, connected by two steel plane webs, traditionally stiffened, vertically and horizontally. The bridge is prestressed by external tendons, normally undulating, anchored in concrete cross-beams on the abutments, and deviated by two cross-beams in the span, also in reinforced concrete. The bridge was launched after complete construction on a prefabrication bed, on one side. The final undulating tendons were straight during launching ; and then detensioned and reinstalled in their final position, one by one, after launching (figures 53, 54).

Dragages et Travaux Publics and Société Générale d'Entreprise joined to build the Arbois bridge over the river Cuisance in Jura [11.6]. This is a small bridge with three spans, made of two concrete slabs connected by two steel trusses, in lieu of the classical webs. In addition, the central rib stiffening the concrete top slab is supported by steel struts, but these central steel elements do not constitute a flexural truss and do not take part in the longitudinal capacity of the bridge. Of course, this bridge is prestressed by longitudinal external tendons, with a now classical lay-out : on each side of the open box-girder, two external tendons are anchored in the extreme concrete cross-beams, on the abutments; and two are anchored in the cross-beam on the abutment on one side, and in the cross-beam on the pier of the other side; symmetrically for the two tendons, to overlap in the main span. These undulating tendons are deviated by the concrete cross-beams on the piers and in the spans. In addition, there is a straight tendon anchored from one abutment to the other (figures 55, 56, 57).

Campenon Bernard also built a three span bridge at Cognac, over the river Charente [11.7]. This time, the concrete webs of the traditional box-girders have been changed to steel folded webs, 8 mm thick. This bridge, built on general scaffolding like the bridge at Arbois, is prestressed by external tendons, all anchored in the concrete cross-beams on the abutments, on each side. These undulating tendons are deviated by the concrete cross-beams on the piers and in the spans, as at Arbois. Due to the very great longitudinal flexibility of the steel folded webs, prestressing forces are concentrated in the concrete slabs, which is evidently efficient and economical. There is no need, in particular, to stiffen the steel webs which have not to support compression forces (figure 58).

These three bridges have been built in experimental conditions by direct agreement between the contractors and the owners – COFIROUTE, a private highway company, for the first of them; and the National Roads Authority (Direction des Routes) for the two others – under SETRA supervision. The fourth bridge – also built for the Direction des Routes – has been contracted after a call for bids that limited the type to this family of structures.

Campenon Bernard won the contract for the Vallon de Maupré bridge, near Charolles, with an original triangular box-girder, the bottom slab being changed to a steel tube, filled with concrete ; and the concrete webs of traditional box-girders being changed to steel folded webs [9, 10, 11.8]. This bridge has been built by the incremental launching method. During construction – on a prefabrication bed on one bank – and launching, the bridge was prestressed by straight, final external tendons, placed just beneath the top slab, and anchored span by span in a transversal

rib stiffening the top slab on the piers. After completion, the prestress was completed by four undulating tendons, anchored in the extreme sections, in the concrete cross-beams on the abutments. These undulating tendons were deviated by steel saddles supported by the steel cross-beams on the piers, and by two steel saddles in each bay, connected to the bottom tube. Due to the great length of these tendons, their tension has been increased by jacking the steel saddles, a computed distance on the central pier (figures 59 to 62).

Some other ideas of the same kind are developing in other countries, such as in Italy.

Prestressing Traditional Composite Bridges

And finally, why not prestress traditional composite bridges ?

The French Code – and others also – don't consider the concrete top slab in the pier zones, where it is in tension. So, more than fifteen years ago, when the first codes had been written for composite bridges, some engineers invented to stress the top slab to avoid this limitation. It has been partly done, at times, by imposing variations in level on the supports to the just completed structure. And some engineers, for instance François Ciolina and Philippe Lecroq, invented to prestress the top slab, in the pier zones, by internal tendons

But it is not so easy to place tendons and anchorages in thin slabs ! External tendons are a much better solution.

We worked on the idea with Gilles Causse, and he designed a solution of this type for the Hospital sur Rhins bridge, over the small river Rhins, near Roanne. Unfortunately, it will not be built: a classical composite bridge was slightly cheaper, and the Owner did not accept the "risk" of an innovative design.

Jean Muller also proposed a solution of this type for the bridge on the river Nive, at Bayonne, but another contractor won the job.

From our experience we can give some preliminary conclusions :

- with a classical lay-out for the external tendons, we develop favourable bending moments and shear force reduction ;
- this shear force reduction allows for reducing the web thickness and the connection ;
- on the other hand, the prestressing forces, if they are too important, can create buckling problems in the webs ; to avoid it, we must not produce compressive forces in the steel beams in the unloaded structure ; we must simply limit tension forces ;
- we cannot reduce the web thickness too much, due to patch-loading problems when launching the steel structure ;
- we conclude that this solution can be applicable only for wide bridges, when the web thickness is relatively important ;
- unfortunately, we cannot take all the advantage of the favourable action of prestressing in flexure, for two reasons : the first being that the concrete slab must be built before tensioning the tendons, so that the structure self-weight must be totally supported by the steel structure ; and the second is that we cannot reduce too much the bottom flange, due to the increasing importance of fatigue specifications ;
- finally, it is not easy to design anchorage elements for this longitudinal prestress, nor the deviation elements.

Contractors devoted to steel construction add that the economy on steel elements is at marginal cost – only the material cost –, and not the addition of tendons, anchorage and deviation elements...

But perhaps steel and concrete contractors could learn to work together. Prestressed composite bridges have already been built in the United States by T.Y. Lin (we don't know exactly how), perhaps in Austria, and surely in Belgium (viaduc du Chatelet) with a design which is not so far from what we imagined.

The coming years will give the final answer.

CONCLUSION

In a seven years time, we have built in France more than thirty bridges in prestressed concrete with external tendons; this number amounts to forty approximately if we add composite bridges - steel-prestressed concrete - built with external tendons at La Ferté Saint-Aubin, Arbois, Cognac, Charolles, and recently near Compiègne.

This gave us an opportunity to develop, step by step, convenient designs adapted to each of the main construction techniques:

- the span-by-span erection technique, segmental or not,
- the cantilever construction method,
- and the incremental launching method.

This has been also an occasion to develop adapted technologies for external prestressing, with many inadequate or uneconomical solutions which had to be abandoned after some experimental applications. This trial and error process has finally led to a limited number of good solutions, the description of which would be out of the theme of this paper.

These last years, practically all large prestressed concrete road bridges have been built in France with external tendons. This demonstrates that, besides and above the impulse of the French Administration in this direction, external prestressing offers great economical advantages for contractors. Now this technique is developed in Germany under the influence of Professor Eibl and in Switzerland; in Belgium, under the influence of René Greisch and Bruno Cremer; and in Czechoslovakia.

Even though we can still progress, in the field of technology mainly, we can state that we master the technique; it is no longer experimental for us, but the normal way of building large concrete bridges.

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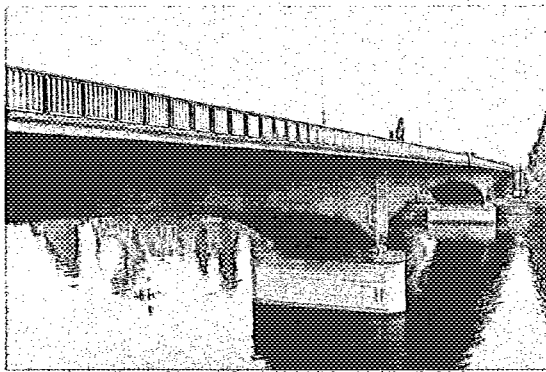


Figure 1: Villeneuve-Saint-Georges bridge (photo J. Chatelain)

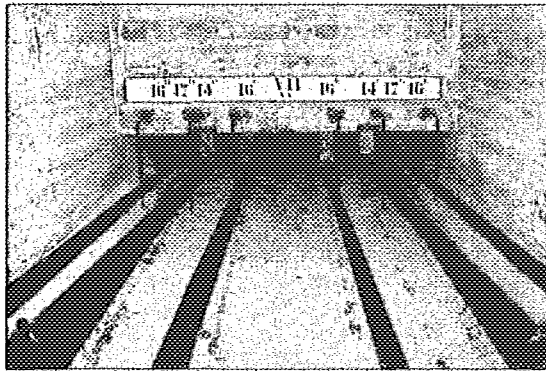


Figure 2: Villeneuve-Saint-Georges bridge. Deviation of external tendons (photo J. Chatelain).

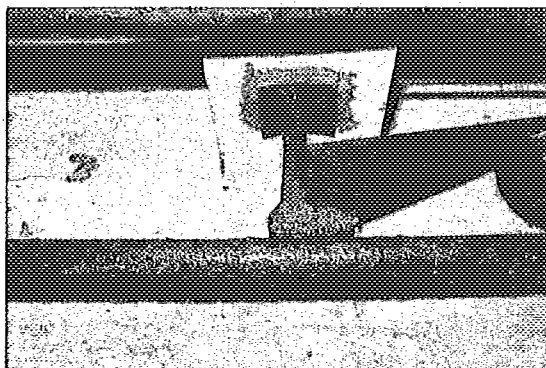


Figure 3: Villeneuve-Saint-Georges bridge. A steel connecting-rod for a cable deviation (photo J. Chatelain).

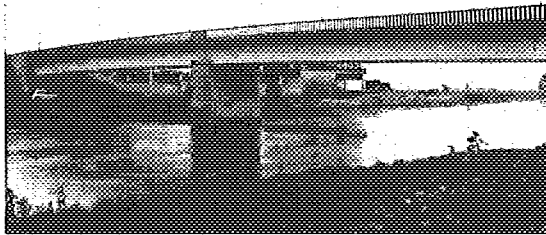


Figure 4 : Port à Binson bridge (photo J. Chatelain).

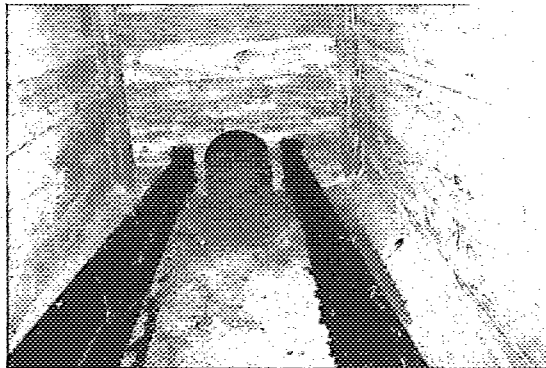


Figure 5 : Port à Binson bridge. External tendons deviated by a concrete diaphragm (photo J. Chatelain).

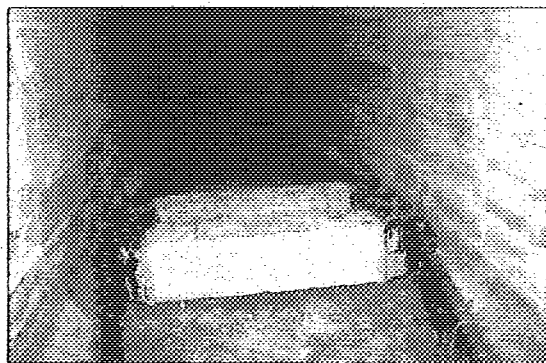


Figure 6: Port à Binson bridge. Concrete blocks and steel braces maintaining the tensioning transverse deviations (photo J. Chatelain).

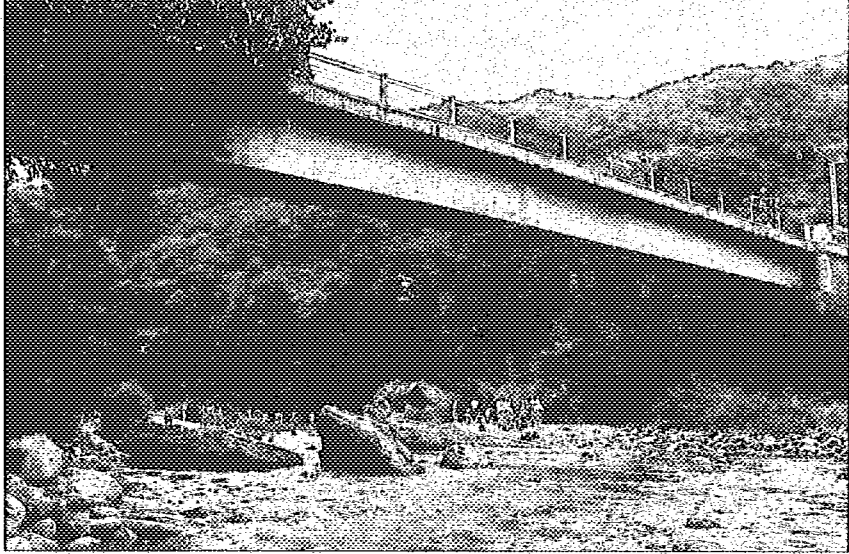


Figure 7: Can Bia bridge (photo M. V.).

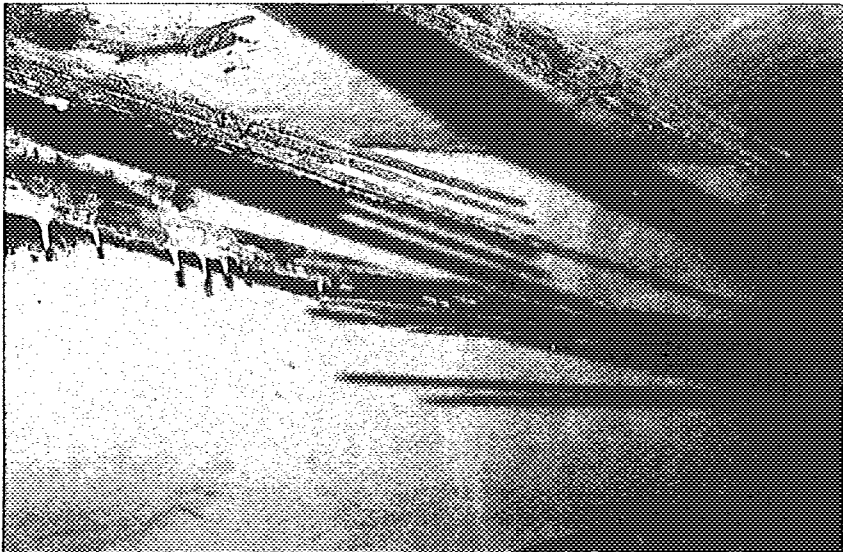


Figure 8: Can Bia bridge. External tendons deeply corroded by water running along wires. Some are broken (photo J. Chatelain).

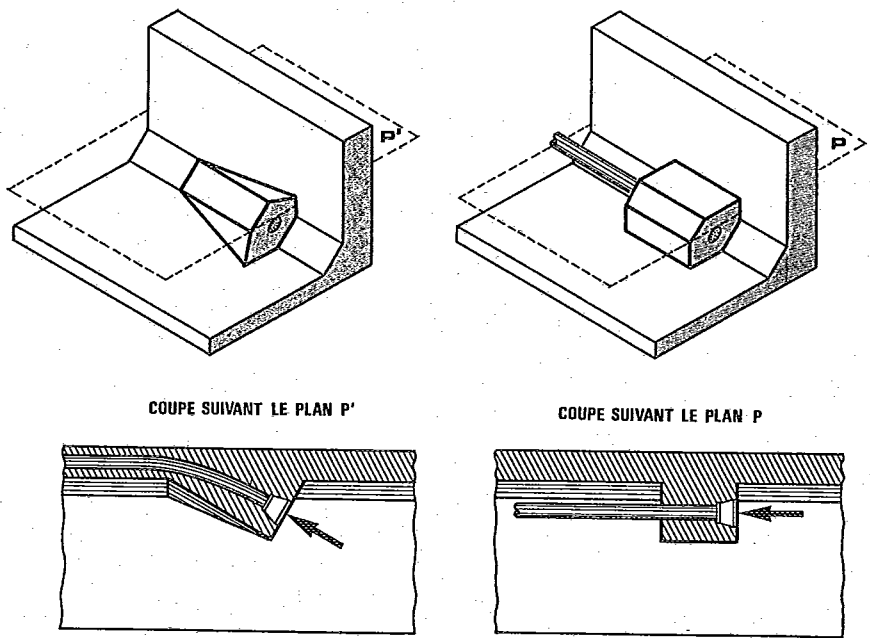


Figure 9: Compared dispositions for the anchorage on a blister of a classical internal tendon (left) and of an external tendon (right).

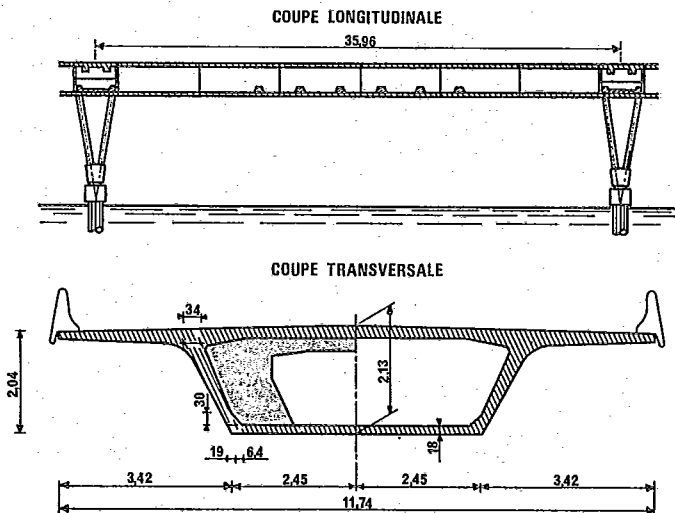
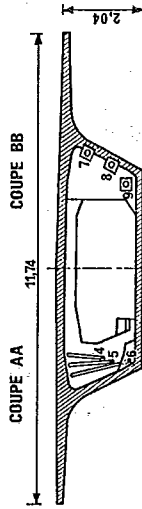
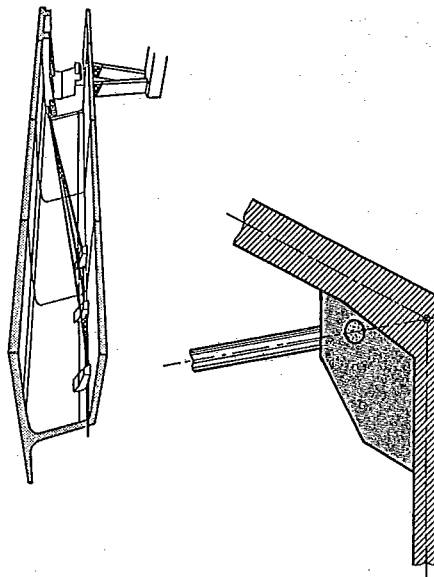


Figure 10: Long Key bridge. Longitudinal section of a typical span. Half cross-sections, on the pier and in the span.

Figure 11: Long Key bridge. Perspective view of the external tendon organization (top, on the left). Principle of a deviation by a small concrete block, with no bending moments in the concrete walls (in the middle, left). Tendon layout : cross section (right), longitudinal view, and view in plan (bottom).



Cables n° 4-5-7-8-9 = 19 T 13
Cable n° 6 = 12 T 13

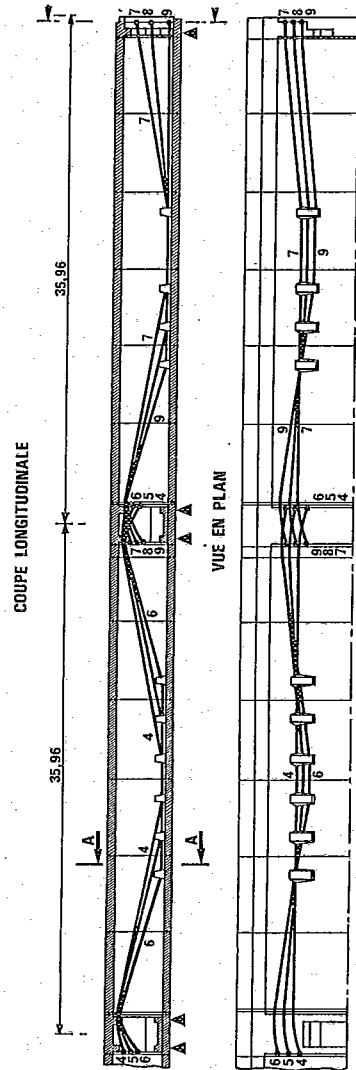




Figure 12: Bubiyan bridge, The erection beam, placing the first segment of the main span (photo M. V.).

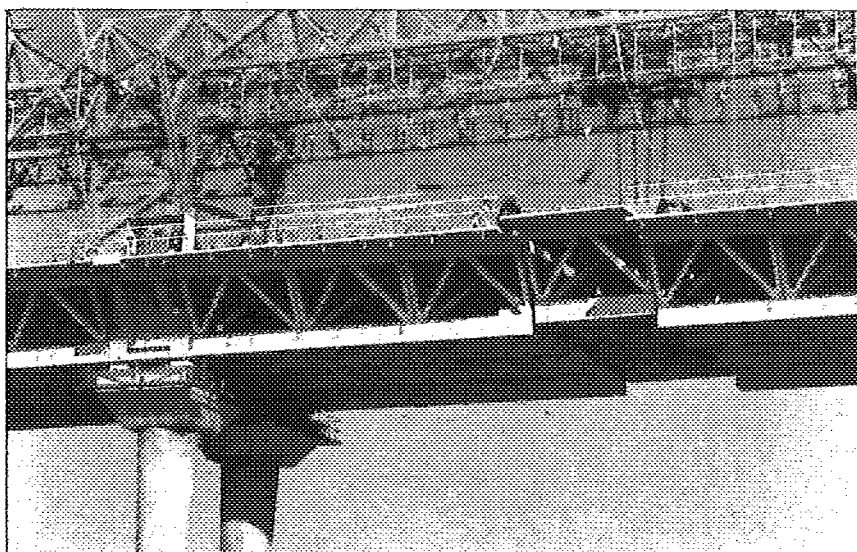


Figure 13: Bubiyan bridge. Placement of the last segment of the main span (photo B. Raspaud).

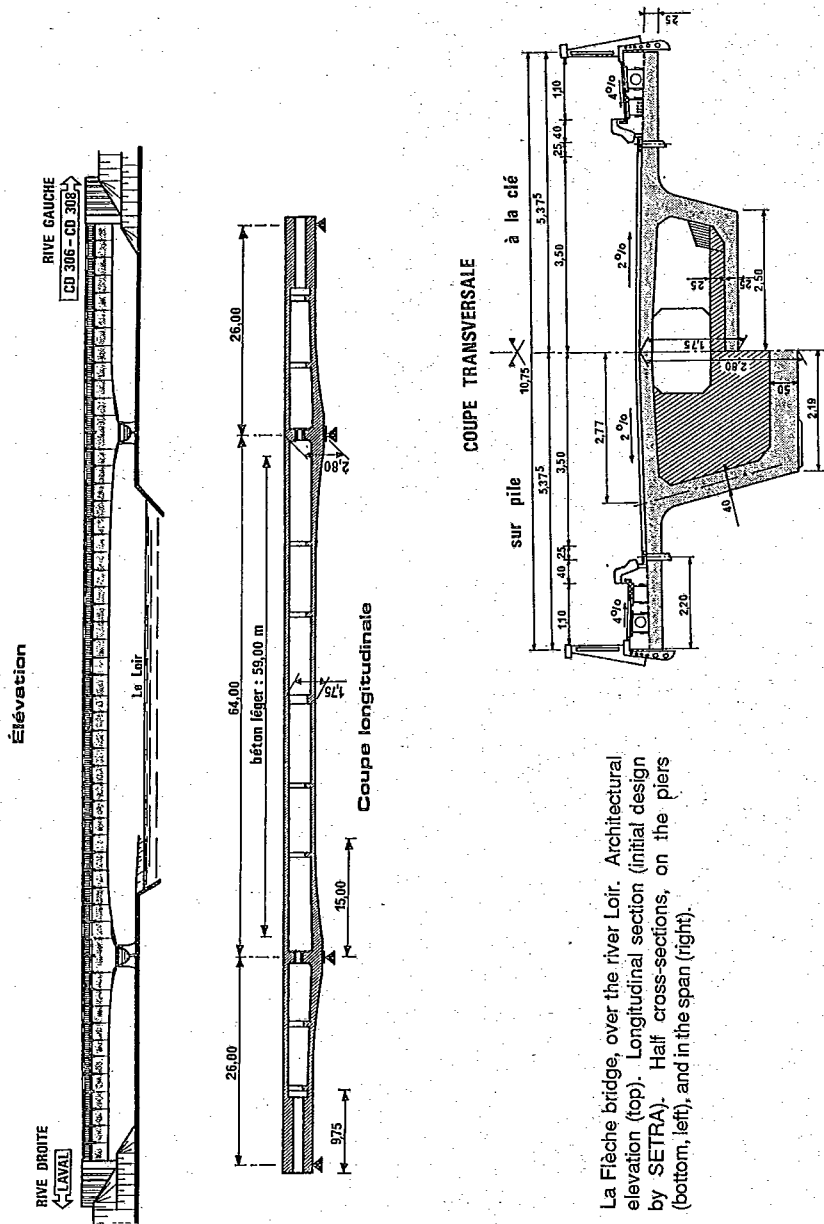


Figure 14: La Flèche bridge, over the river Loir. Architectural elevation (top). Longitudinal section (initial design by SETRA). Half cross-sections, on the piers (bottom, left), and in the span (right).

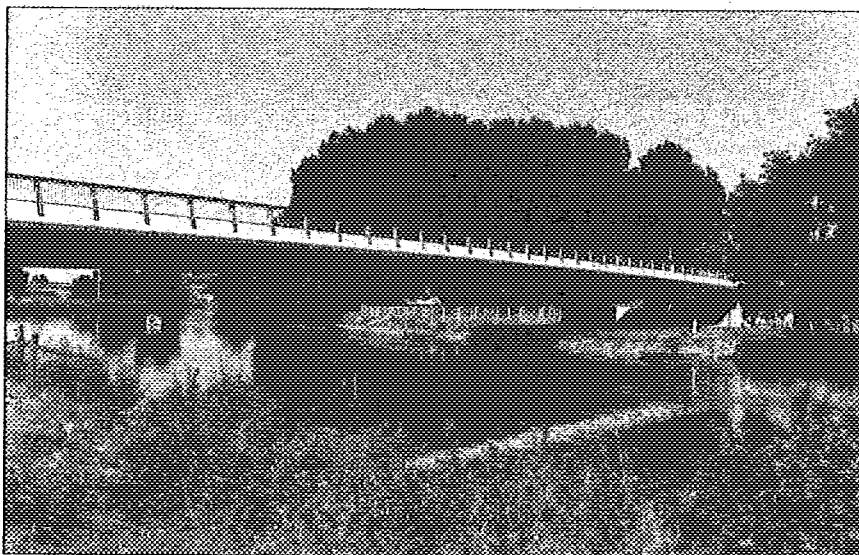


Figure 16: La Flèche bridge over the river Loir (photo M.V.).

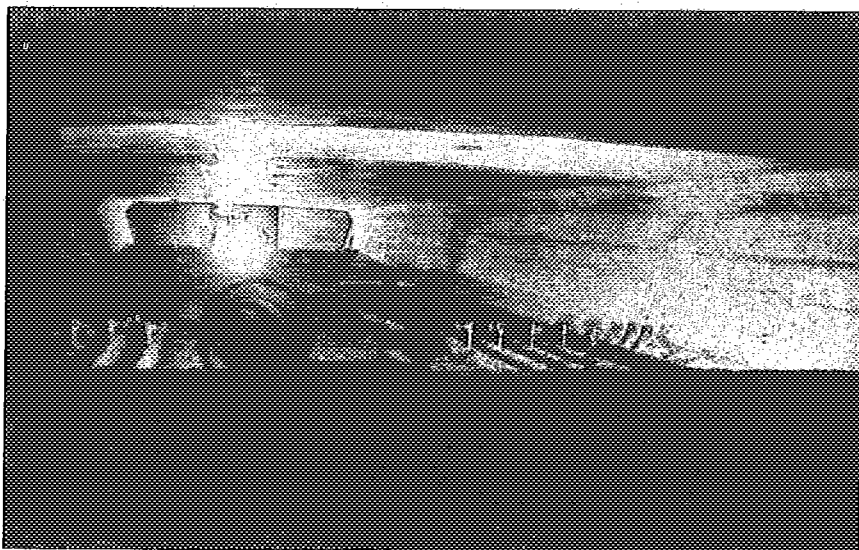


Figure 17: La Flèche bridge. Internal view of the box-girder, with the eight external tendons and the two empty ducts (photo M. V.).

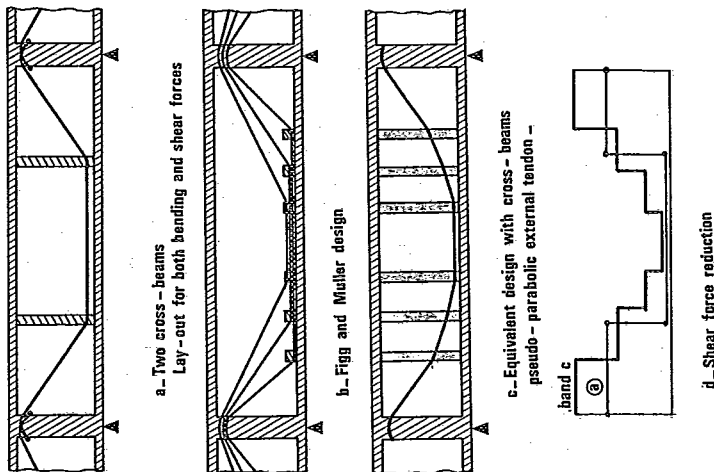


Figure 18: Tendon arrangement for box-girders of constant height: two deviations per bay; tendons radiating from the cross-beams on the piers; multiple deviation diaphragms leading to a pseudo-parabolic layout; and shear force reduction.

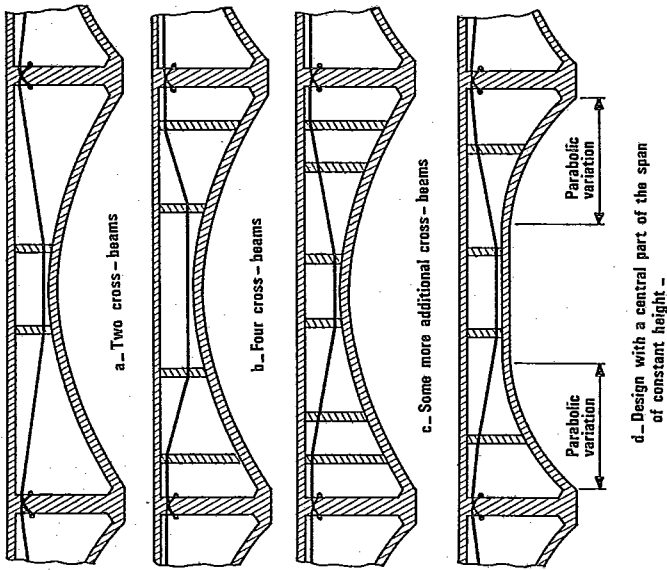


Figure 19: Tendon arrangement for box-girders of variable height: two deviation cross-beams per bay, for a parabolically varying height; and four deviation cross-beams; amendment of the height variation, with a central part of the span of constant height.

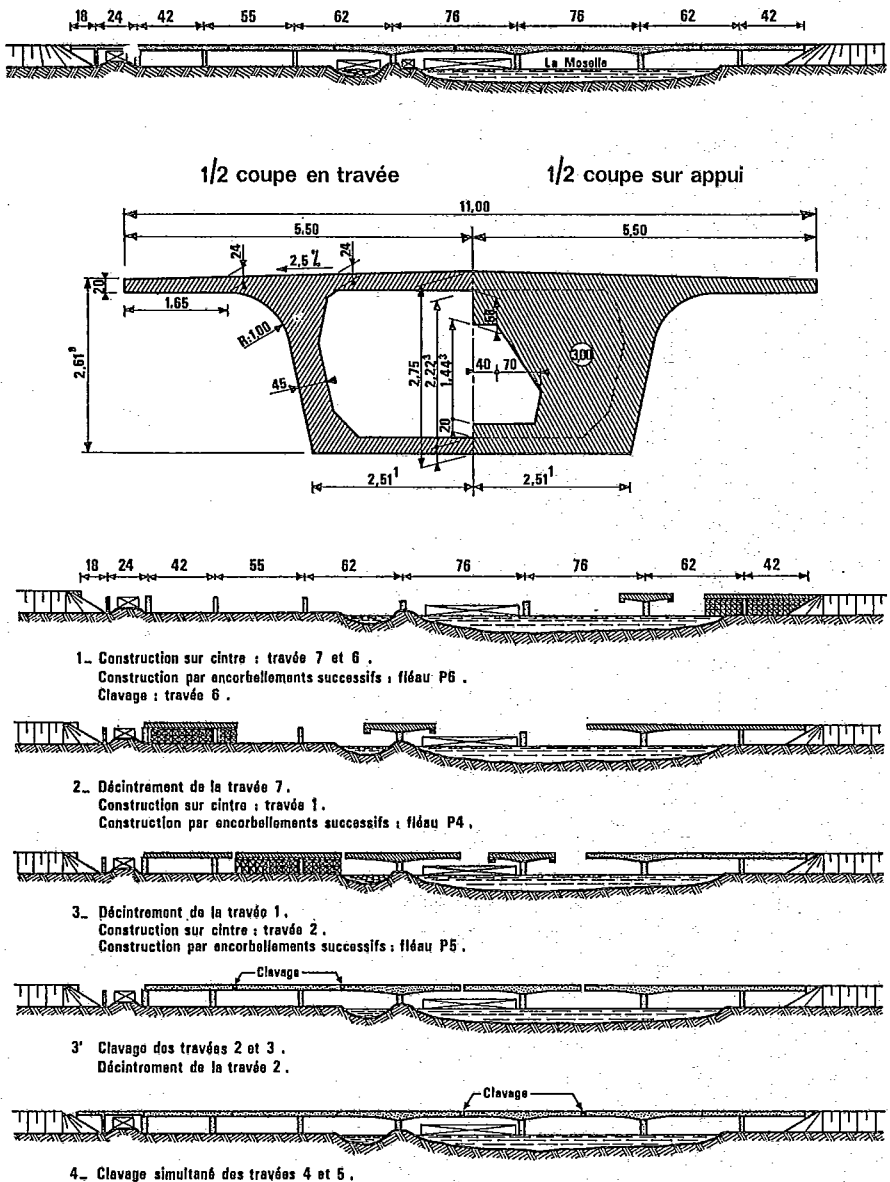


Figure 20: Pont à Mousson viaduct over the river Moselle. Longitudinal view (top). Half cross-sections, in the spans (left) and on the piers (right) of the bays of constant height. Construction sequences (bottom).

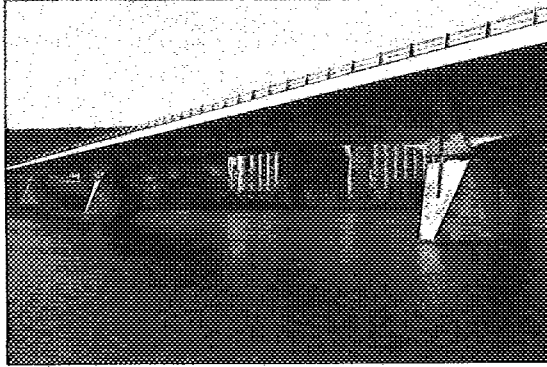


Figure 21 : Pont à Mousson viaduct (photo M. V.).

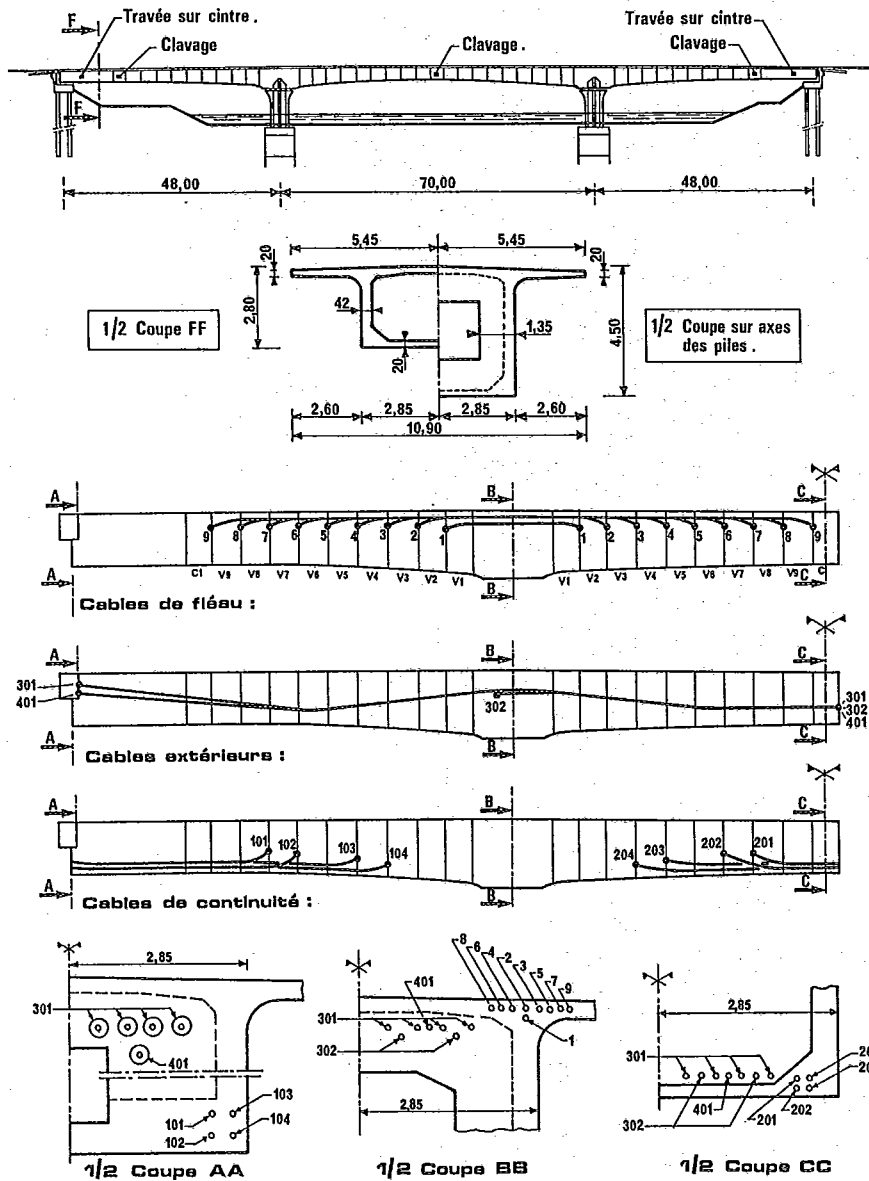
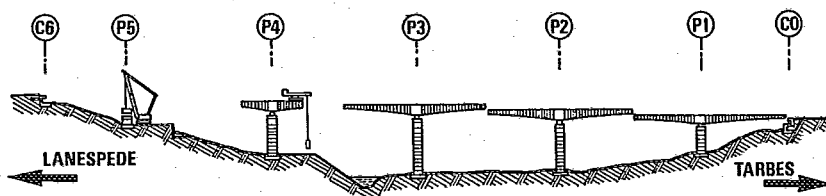
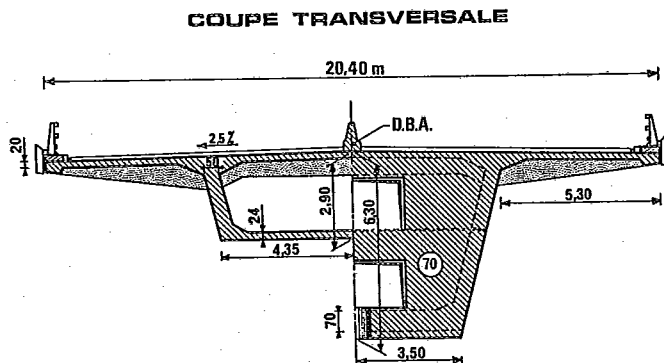
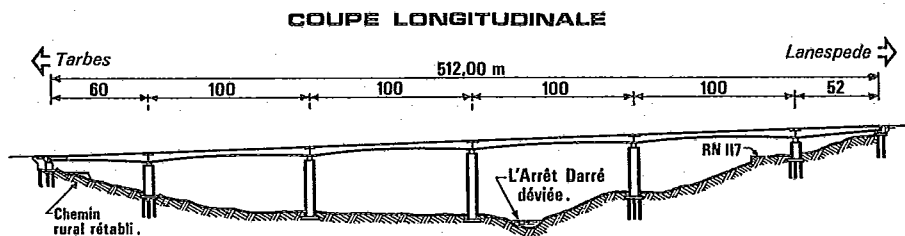
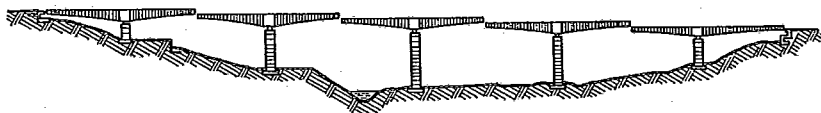


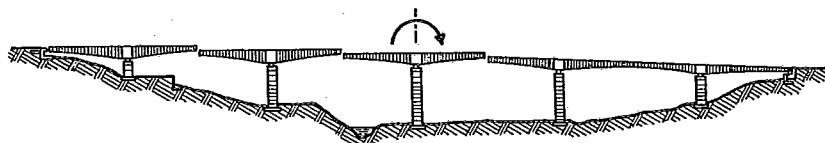
Figure 22: Chinon bridge over the river Vienne. Longitudinal view (top). Half cross-sections, in the span (left) and on the piers (right). Tendon layout: longitudinal views of the tendons, cantilever internal tendons (top), continuity internal tendons (middle) and external tendons (bottom); cross-sections.



1. Construction des piles à la grue, au moyen de voussoirs préfabriqués -
- Construction des fléaux par encorbellements successifs au moyen de voussoirs préfabriqués, à l'aide d'une potence de levage mobile -



2. Achèvement de la construction des fléaux, à l'horizontale -



3. Basculement des fléaux et clavages -

Figure 23: The Arrêt Darré viaduct. Longitudinal view (top). Half cross-sections, in the spans (left) and on the piers (right). Construction sequences (bottom).

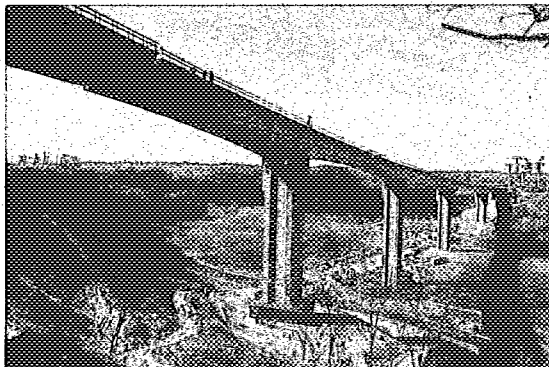


Figure 24: The Arrêt Darré viaduct. The cantilevers have been built with precast segments limited to the box itself; and they have been rotated to their final position (photo Cl. Servant).



Figure 25: The Arrêt Darré viaduct. Construction in situ of the lateral parts of the top slab (photo Cl. Servant).

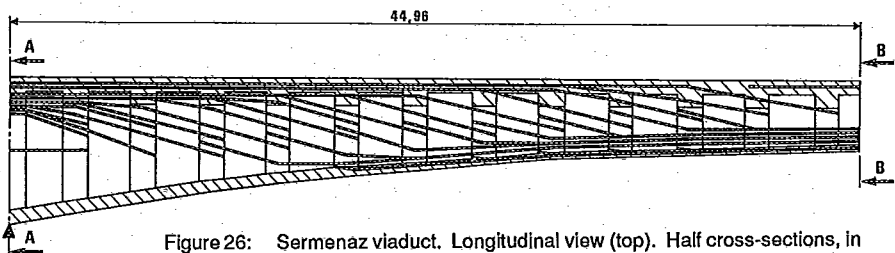
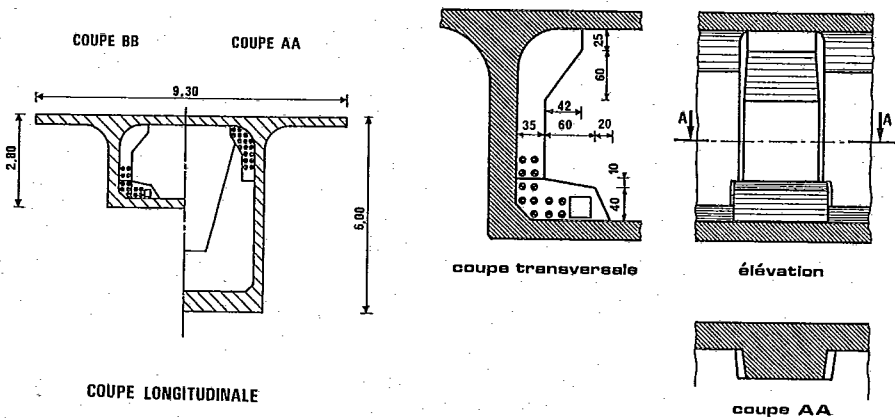
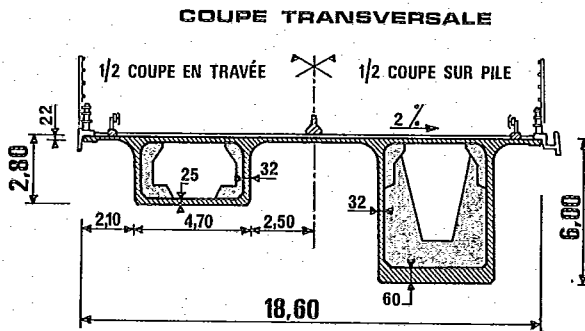
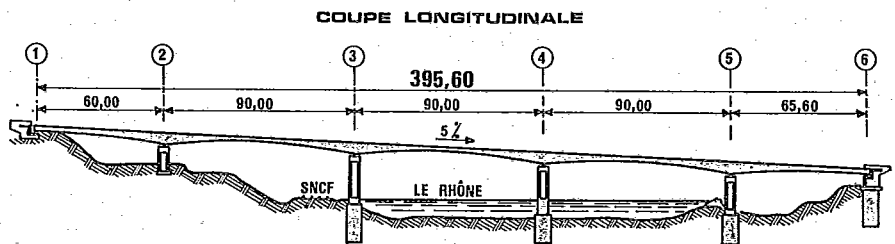


Figure 26: Sermenaz viaduct. Longitudinal view (top). Half cross-sections, in the spans (left) and on the piers (right). Longitudinal view (bottom) and cross-sections (left) of the tendon layout. Details of the vertical ribs used for anchoring and deviating external tendons (right).

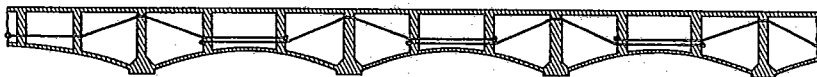


Figure 27: Another principle for the tendon layout: external tendons anchored in the spans and overlapping in the key-zones.

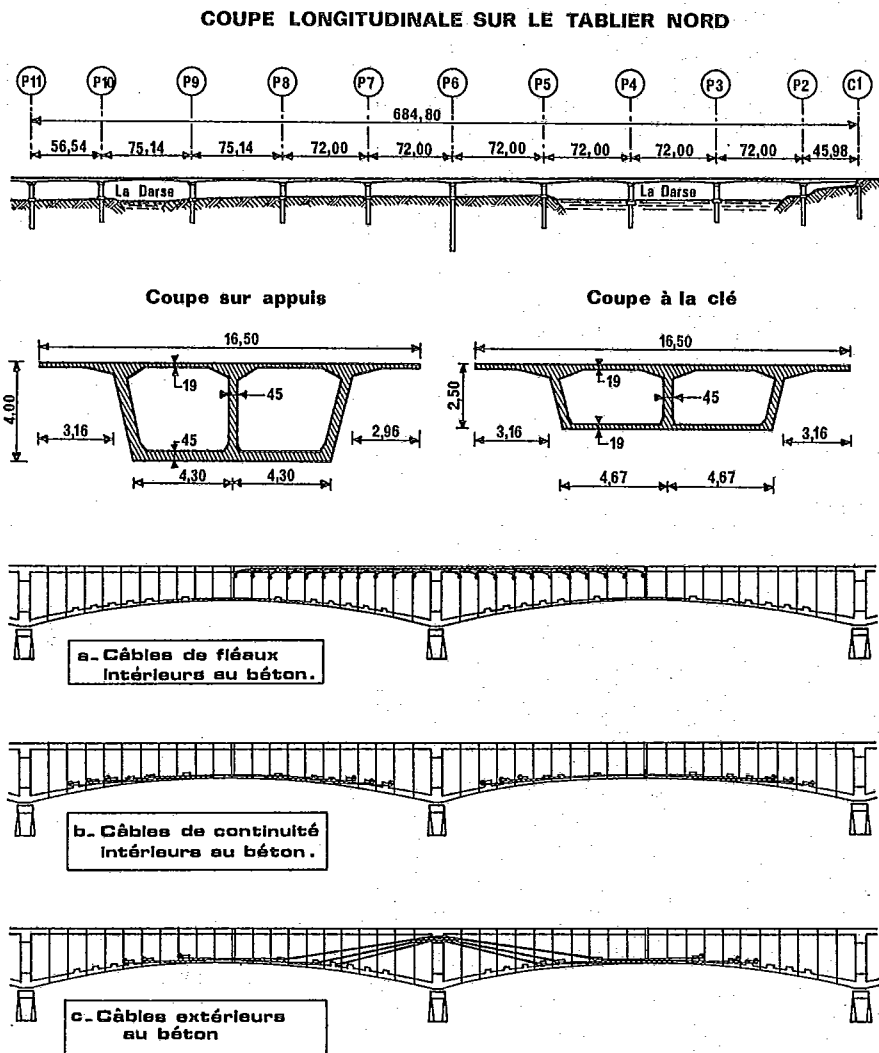


Figure 28: Darse du Gaz de France viaduct in Alfortville. Longitudinal view (top). Half cross-sections (the bridge is made of two parallel box-girders), on the piers (left) and in the spans (right). Tendon arrangement in typical spans: internal cantilever tendons; continuity internal tendons; external tendons.

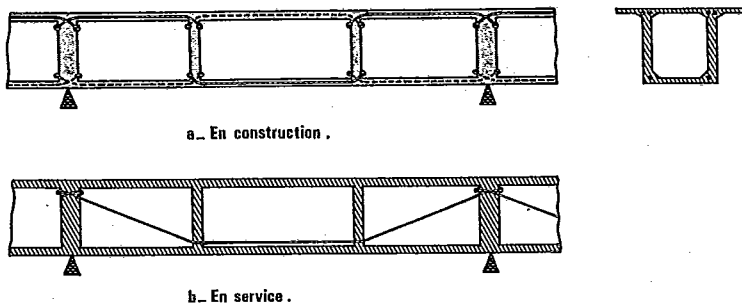


Figure 29: Principle of the mixed prestressing design for bridges built by the incremental launching method: internal straight tendons before construction, in the nodes (top); and external tendons after launching (bottom).

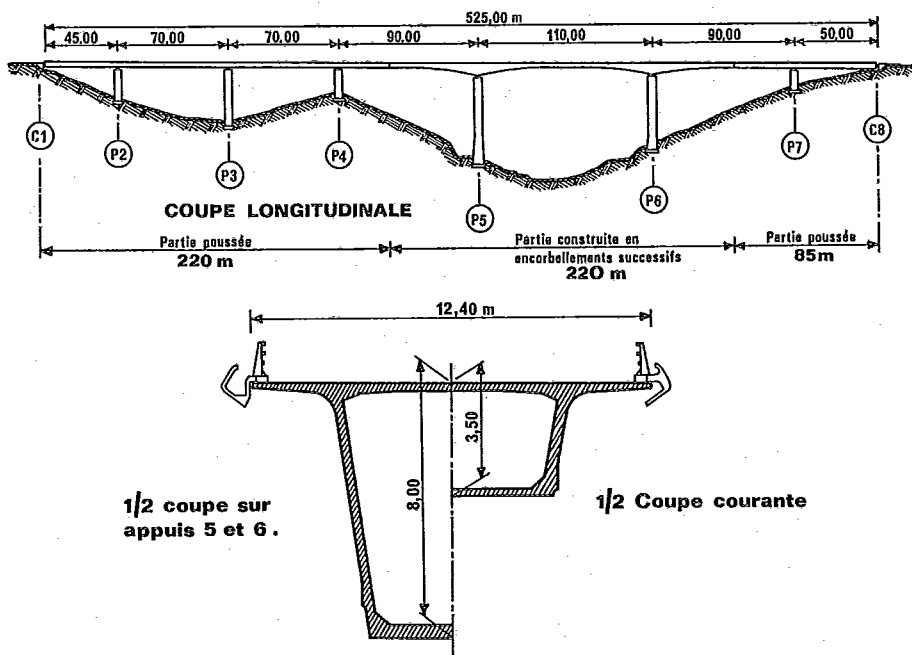


Figure 30: Roquebillère viaduct, near Cahors. Longitudinal view (top). Half cross-sections, on the two main piers (left), and in the spans (right).