Combining prestressed concrete and steel for bridge construction

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Combining Prestressed Concrete and Steel for Bridge Construction

Les ponts mixtes associant l'acier et le béton précontraint

Vereinigung von Spannbeton und Stahl im Brückenbau

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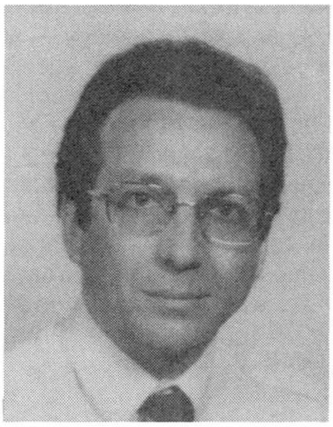

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SUMMARY

It is now classical to build bridges comprising a steel structure with a concrete deck. The technical evolution, and the development of Computer-Aided Fabrication made these structures extremely economical. But this paper aims at describing other solutions for an efficient combination of prestressed concrete and steel in bridge construction.

RESUME

Les ponts mixtes – constitués d'une charpente métallique et d'une dalle de couverture en béton – sont aujourd'hui devenus courants. L'évolution technique et le développement de la Fabrication Assistée par Ordinateur ont rendu ces structures particulièrement économiques. Mais cet article a pour but de décrire d'autres solutions d'associations de l'acier et du béton précontraint.

ZUSAMMENFASSUNG

Die klassische Verbundbauweise kombiniert ein Stahltragwerk mit einer Betonfahrbahnplatte. Die technische Entwicklung, vor allem in der computerunterstützten Fertigung, hat diese Bauweise äusserst wirtschaftlich werden lassen. Darüber hinaus gibt es jedoch andere Kombinationsmöglichkeiten, die der folgende Beitrag vorstellen will.

1. INTRODUCTION

The past ten years have seen the development all over the world of cable-stayed bridges, either with prestressed concrete or with composite decks, of external prestressing and of high strength concrete. But, due to the fantastic development of technical medias – including international associations –, the evolution to these new solutions has been both rapid and progressive.

The development of bridge construction does not leave much place to a real technical revolution, in our personal opinion, as those produced in the nineteenth century by the explosion of steel construction and later by the development of reinforced concrete, or in our century by the development of prestressed concrete and later of prefabrication.

Innovation will progress by limited steps, from the evolution of materials themselves – such as high strength steel and high strength concrete –, and of technology – as for external prestressing and for corrosion-protected stays. But also from the development of our knowledge on the actions applied to structures, such as seismic and wind effects, which will allow for the construction of very large spans: the East Bridge of the Storebaelt Link in Denmark (1624 m) and the Akashi Straight Bridge in Japan (1990 m) will give the way for suspension bridges, and the Pont de Normandie (856 m) will open a new span range for cable-stayed bridges; all of them allowed by a better knowledge of wind forces.

In this situation engineers will have to be more modest as regards innovation, and turn most of their efforts to the best use of existing materials, techniques and technologies in order to obtain economy, æsthetical elegance, durability and capacity for maintenance; that is to say quality in all its aspects.

One of the ways for this limited progress is a wider association of steel and prestressed concrete.

2. COMPOSITE CROSS-SECTIONS

Of course, the idea of associating steel and concrete in a bridge cross-section is now classical. The technical progress but also the development of Computer-Aided Design and of Computer-Aided Fabrication gave to composite structures great economical advantages, and they are now in France much ahead of prestressed concrete bridges for medium-size spans, from 40 to 80 metres, as soon as the steel structure can be economically launched.

Despite this success, engineers still try to improve the solution.

2.1. Improvement of classical composite structures

The last 15 years produced a great simplification of the steel structure: only two main beams, except when it is not feasible; use of very thick flanges (up to 150 mm in France); limitation of the number of cross-beams, generally not connected to the concrete slab; reduction of stiffening elements. All these factors limited the length of welds and through this the working time and cost.

In consequence, typical composite bridges are now made of two I-shaped beams, connected by cross-beams and supporting a reinforced concrete top slab. Only very wide decks have a different structure: with a transversally prestressed concrete top slab, or with cross-beams supporting a reinforced concrete top slab. Exceptionnally, for very curved bridges or for æsthetical purpose, the steel structure constitutes with the concrete top slab a box-girder.

The most controversial point regards the slab construction. In the classical solution, the slab is cast in situ on a mobile carriage supported by the steel structure, already launched. The construction sequence is organized to limit tensile stresses on supports. But the use of prefabricated elements is developing, not always in the best way for durability.

New ideas are under development for a better solution:

- launching the deck with its slab already concreted on the prefabrication area; but, of course, this method increases the weight of the structure during launching, and from this bending moments during launching, and also launching reactions on supports which can produce web instability;
- launching on the steel structure – already placed – a prefabricated slab which will be later connected to the beam top-flanges; this solution allows for a longitudinal prestressing of the top slab, extremely favourable for its durability;
- incorporation to the steel structure of a folded steel plate, later used as a lost shutter for concreting the top slab; unfortunately, standard folded steel plates used in the building industry have not, generally, the necessary capacity to span the distance between beams or cross-beams, and their connection to the steel top-flanges is far from perfect as regards waterproofness.

2.2. New attempts

With the help of S.E.T.R.A., some concrete contractors attempted in France, between 1982 and 1985, to develop a new concept by replacing the classical webs of concrete box-girders by steel webs, in order to lighten concrete structures. Of course, these new composite box-girders were prestressed, with external tendons to produce also shear-force reduction.

- The first example is the La Ferté Saint-Aubin bridge, over the A.71 motorway, built by Fougerolle: the concrete webs have been replaced there by plane steel webs, strongly stiffened to enable them to carry the compressive forces produced by the external tendons.
- The second example is the Arbois Bridge over the river Cuisance, in Jura, built by Dragages et Travaux Publics and Société Générale d'Entreprise (SOGEA): the two concrete webs have been replaced by two plane steel trusses (figure 1). In addition, some steel struts support a central rib in the top slab, but they don't participate in the flexural rigidity.
- The third example is the Cognac Bridge, over the river Charente, built by Campenon-Bernard: the two concrete webs have been replaced by two folded steel webs which don't carry any longitudinal compression (figure 2). The prestressing efficiency is thus increased, and we consider accordingly that this solution is certainly the best.
- The last example has been the Val de Maupré Viaduct, near Charolles, also built by Campenon-Bernard (figure 3). In this case, the two folded steel webs give to the box-girder a triangular shape, and the concrete bottom flange is replaced by a steel tube filled with concrete. In fact, this concrete is only used during launching to distribute the reaction on the supports and to endow the tube with the necessary stability.

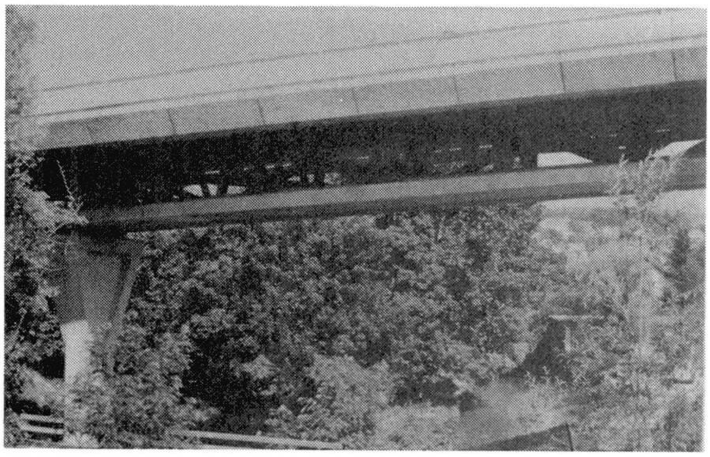

Figure 1: The Arbois Bridge, over the River Cuisance *(photo D. Le Faucheur)*

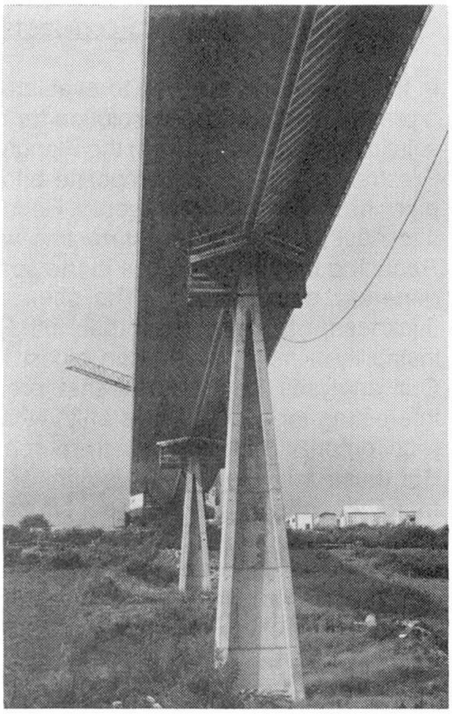

Figure 3: The Val de Maupré viaduct, at Charolles, during erection *(photo G. Forquet)*

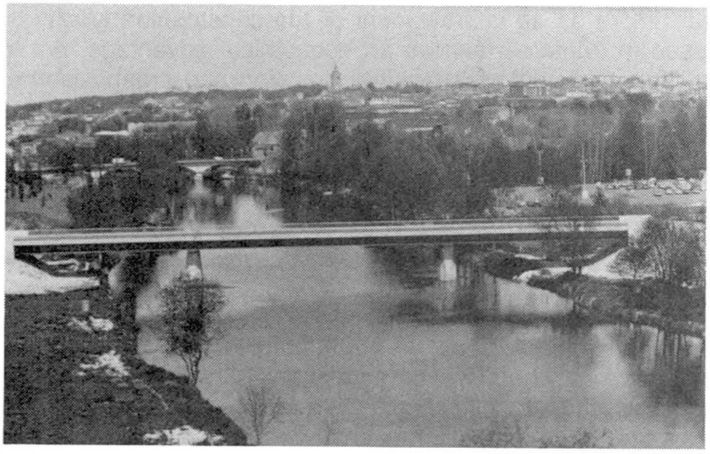

Figure 2: The Cognac Bridge, over the River Charente *(photo G. Forquet)*

Unfortunately, these four experimental bridges, contracted in special conditions (by direct agreement in the first three cases, and after a competition limited to this type of structures for the last one), evidenced a very limited economical interest: during the time of their design and construction, the "classical" prestressed concrete and composite structures also evolved and finally proved more economic. It must be said that the cooperation between steel and concrete industries did not appear easy, and that their association creates some additional cost; not forgetting all the small details which have been evidenced by these experimental constructions and which had to be solved by rather expensive solutions. Even if some progress is still possible to limit their cost, we don't think that we have here very promising ideas.

Due to this, very few bridges have been built according to these ideas in normal competition conditions. All of them follow the way evidenced by the Val de Maupré viaduct: the concrete bottom flange is too heavy and must be avoided; and thus the prestressing forces are no more necessary. Consequently, these bridges are made of a steel structure supporting a reinforced concrete top slab, without concrete bottom slab; nor prestressing tendons for the first two:

- The Asterix Park Bridge, over the A.1 motorway, has been built by Campenon-Bernard and Eiffel Constructions Métalliques (C.F.E.M.); it is constituted of two isostatic spans, each of them made of two folded steel webs supporting a reinforced concrete top slab, with cross-beams on supports only.
- The Saint-Pierre Bridge, over the river Garonne in Toulouse, has been built by Campenon-Bernard after a design and build competition, mainly oriented by architectural considerations; it has a very old-fashioned aspect: this three-span bridge is made of two steel truss beams, of variable height, supporting a reinforced concrete slab.
- The last example is an experimental bridge again, designed by Jean Muller. The Roize Bridge, over the A.49 motorway, is a steel spatial truss supporting a reinforced concrete top-slab; it is prestressed by some external tendons, as the first bridges built before 1985. But we doubt about its economical interest in open competition with classical composite structures.

2.3. Prestressing classical composite structures

In the same time, we tried to evaluate the interest of prestressing classical composite bridges. We designed a prestressed composite solution for the Hopital sur Rins Bridge, in the Loire district, and we are designing a solution of the same type for the Planchette viaduct, on the A.75 motorway.

Prestressing classical composite bridges with undulated external tendons, spanning each bay from pier to pier, has some advantages. Reducing the flexion forces on supports limits the beam bottom flange thickness; this can be interesting when this thickness becomes very great (more than 100 or 120 mm). Reducing the flexion forces in the spans has a more limited interest, because the bottom flange thickness is generally more limited. The shear-force reduction produced by the external tendons can limit the web thickness; but, on the other hand, the compression produced by the tendons increases the risks of instability in the webs, and can impose some thickness increase.

Our analyses have shown that prestressing classical composite bridges with external tendons can be interesting for wide bridges only, when the web thickness is governed by shear forces and not by minimum requirements, and also when the beam bottom flanges are very thick.

But these analyses have also shown that the economical interest cannot be very high, if there is any: the marginal economy in the steel structure is concentrated on supports and near mid-spans; and we have to pay continuous tendons. It becomes clear that the sole interest can be a much better distribution of forces in the concrete slab: under the effect of permanent loads, a much more limited zone around supports will be under tension and thus cracked.

Prestressing classical composite bridges appears more as an improvement of the construction quality – mainly in areas where de-icing salt is widely used in Winter – than as an economical advantage, not to mention the problems arisen from the detailing of the external prestressing: location and organization of anchorages; design of deviation cross-beams... Again, it appears that technical progress is not easy, and that engineers must remain modest and humble.

3. COMPOSITE BRIDGES, LONGITUDINALLY

If it is classical to associate steel and concrete in the bridge cross-section, it is also possible to distribute steel and concrete in the bridge length, in order to take advantage of the difference in weight between these two materials.

This idea came from the development of lightweight concrete bridges in the Netherlands and in France at the beginning of the seventies. The Dutch engineers, from whom we drew inspiration, built in lightweight concrete the main span of some three-span bridges, such as in Nijmeguen. These lightened central spans could then be balanced by rather short side-spans built in traditional concrete. We applied this principle to the construction by the cantilever method of the Ottmarsheim Bridge, over the Alsace Canal, and of the Tricastin Bridge over the Donzère Canal; but also to the construction of two small cable-stayed bridges: the pedestrian bridges at Meylan, over the river Isère, and at Illhof, over the river Ill.

3.1. Steel isostatic spans supported by concrete cantilevers

Two bridges have been built in France, designed by S.E.T.R.A., with a steel isostatic span supported by prestressed concrete cantilevers.

At the beginning of the seventies, François Ciolina designed the Ile Lacroix Bridge, over the River Seine in Rouen: each of the two arms of the river is crossed by a steel isostatic span, supported on one side by a concrete cantilever extending a prestressed concrete structure on the central island (figures 4 and 5). The steel spans are made of two I-shaped beams connected by an orthotropic top slab. The great difference in weight between these steel structures and the central concrete box-girder avoids any uplift reaction on the supports on the island. And it has been possible to build in steel a structure much thinner over the river than we could have done in prestressed concrete. In addition, it has been extremely easy to build the steel spans in a factory – located in Rouen at that time –, to load each of them on a barge, and to place them in their final position by just ballasting the barges.

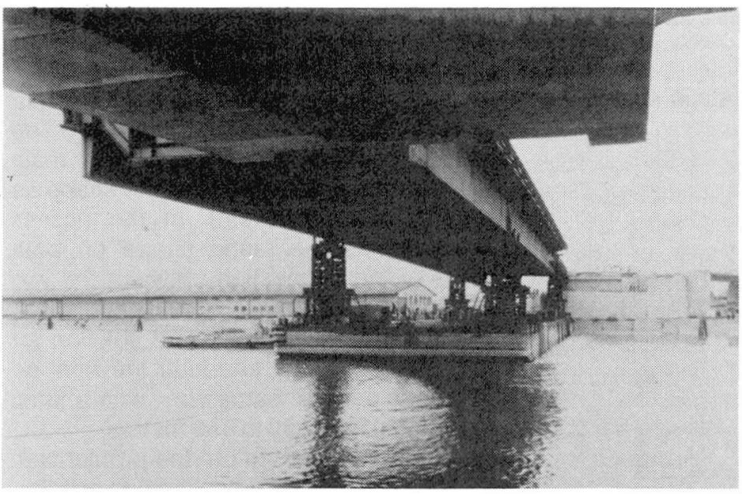

Figure 4: The Queen Mathilde Bridge, at Rouen; an isostatic span is placed from a barge on its cantilever supports *(photo D.D.E. of Seine-Maritime)*

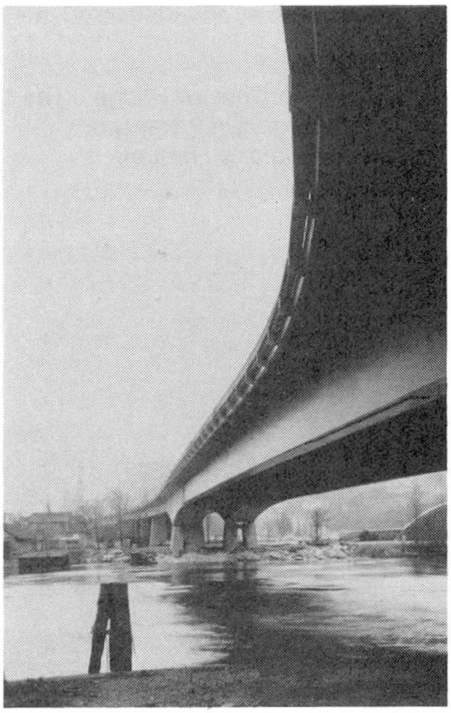

Figure 5: The Queen Mathilde Bridge, after completion *(photo D.D.E. of Seine-Maritime)*

We did practically the same for the Cheviré Bridge, over the River Loire in Nantes, following an idea by Charles Brignon. The isostatic span is then a wide box-girder, with an orthotropic slab, with the same external shape as the prestressed concrete viaducts on the two sides (figures 6 and 7). The height of the concrete box-girder which constitutes the cantilevers supporting the steel span is limited to 8.0 m on the main supports. It would have been greater by three or four metres if the bridge had been built in concrete only, with a main span 242 m long. And due to the presence of the Nantes Airport, in the bridge axis, it was not possible to place the high pylons of a classical cable-stayed bridge.

There again, the difference in weight, between the steel and the concrete parts of the bridge, avoids any uplift reaction in the access spans, despite the great differences in span lengths.

As in the Ile Lacroix Bridge, the central steel span has been built on a bank of the river, placed on a barge, then lifted from the concrete cantilevers with the help of a series of prestressing tendons and jacks.

3.2. Cable-stayed bridges with a steel main span

The same principle applies to cable-stayed bridges. But, once again, at first we designed a bridge with both lightweight and traditionnal concretes, which has not been built: the Elbeuf Bridge project has a single pylon in the alignment of an island, and the cables support from it a main span in lightweight concrete over the river Seine; the access spans, on the other side, in traditional concrete, are supported by many piers in a dead arm of the river Eure. These numerous piers are necessary to balance the difference in weight between traditionnal and lightweight concretes; they also allow for a construction of the access spans by incremental launching; only the main span is built by the cantilever method, with one single mobile carriage. And the

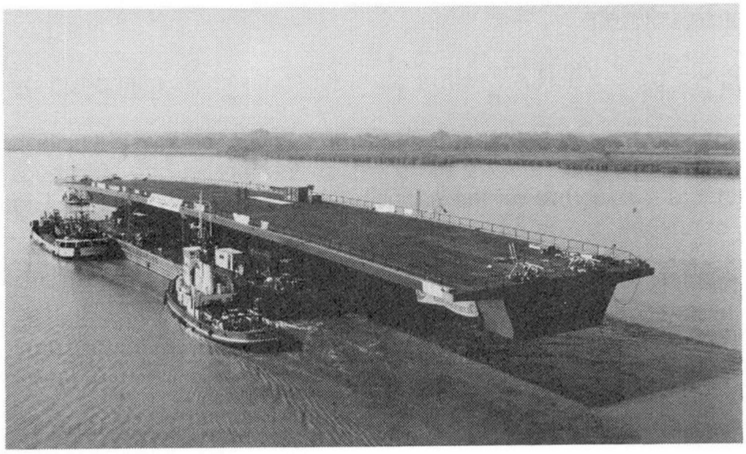

Figure 6: The Cheviré Bridge. The steel isostatic span on its barge during transport
(photo G. Forquet)

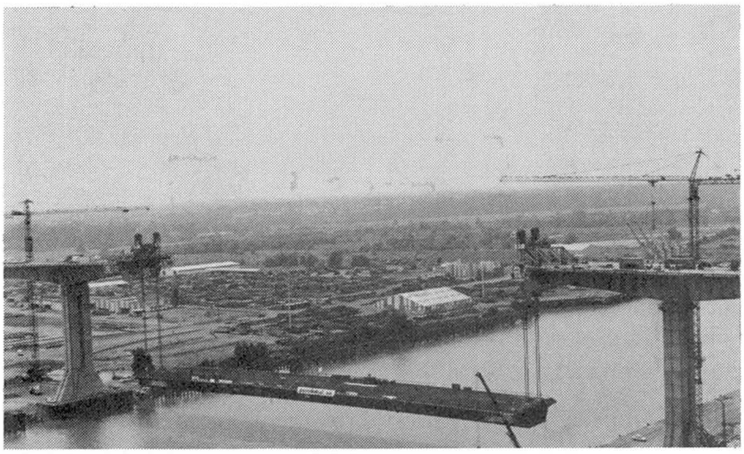

Figure 7: The Cheviré Bridge: the steel isostatic span is now lifted from the two concrete cantilevers
(photo G. Forquet)

difference in weight between the two concretes avoids any uplift reaction on the supports, with the help of thicker webs in the access spans.

The original design for the Seyssel Bridge obeyed to the same principles. And we designed a cable-stayed solution for the Beaucaire Bridge, over the river Rhone, with a unique steel cable-stayed span over the navigable part of the river, balanced by concrete access spans, on close supports, on the other side of the Bartelasse Island.

These ideas were perfectly developed by the Mexican engineers who designed the Tampico Bridge, the detailing of which has been done by Sogelerg: a steel main span is balanced by concrete access spans on close supports. The box-girder – orthotropic in the main span, in concrete with the same shape as in the Brotonne Bridge in the access spans – has the same shape on both sides of the connection between the two materials.

We designed a cable-stayed solution for the Cheviré Bridge and later the Pont de Normandie in the same way, with a jump in the span from 360 to 856 metres.

We just have to point out the problems at the connection. It is necessary to distribute prestressing bars to fix the steel structure to the concrete one, in order to balance both general and local forces. And it is necessary to slightly amend the orthotropic slab profile, to drive compressive forces to the gravity center of the concrete slab and not at its top fiber.

In our opinion, this solution is extremely efficient and gives the bridge a very good capacity to support important wind forces.

4. COMPOSITE DECKS FOR ARCH BRIDGES

The last idea concerns arch-bridges.

The design of the arch bridge over the river Rance, in French Brittany, evidenced very difficult problems: the arch had to be very slender (a vertical distance of 32 m for an opening of 260 m). Fearing some stability problems, we wanted to create a central node connecting the deck to the arch; but this solution had two handicaps:

- it creates a discontinuity in the arch central line, and from it important flexion forces at the central node limits, due to the important normal force;
- it makes the construction more complicated.

We decided to avoid this central node, but wanted to reduce the deck weight to limit stability problems. We thought of lightweight concrete, and finally with Jacques Mathivat we considered that the best solution was a composite deck, much lighter than a traditional concrete deck (figures 8, 9 and 10).

This deck is made of two I-shaped beams connected by cross-beams, and supporting the reinforced concrete top slab.

But the reduction in weight (from about 16 to 10 metric tons per metre, excluding the equipments) is not the sole advantage of a composite deck. It is also extremely favourable to place the deck weight progressively.

It is clear that local loads on an arch are extremely unfavourable. Thus, it is very unfavourable to build the deck span by span, or to launch it. It is at least necessary to help the arch during such operations with temporary cables, as we did when we launched the deck over the Trellins arch, over the river Isère, or as was done for the bridge in the Neckar valley in Germany.

The classical solution consists in constituting the deck with precast I-shaped beams in prestressed concrete. One beam is at first placed in each span; then a second one; and then the third one; and so on. As it was done, for example, for the three beams constituting each span of the deck for the Kerk arch bridges in Yugoslavia. This progressive installation limits the difference in weight between the different spans, and from this the bending forces produced in the arch.

A composite deck presents the same advantages: the steel structure is first launched; its light weight – about 2.5 metric tons in the case of the bridge over the river Rance – creates no problem. Then the reinforced concrete slab can be concreted. But we can organize the sequence to avoid major problems: by concreting symetrically at first, from the arch midspan to the springings; and with more complicated sequences if necessary, with a better load distribution, still symetrical.

The experience of the construction of the arch bridge over the river Rance evidenced such advantages that we really don't understand why this solution has never been used before.

We began to design another arch bridge, at La Roche-Bernard over the river Villaine, and again with S.E.C.O.A. We have not hesitated one single second and immediately selected for the deck a composite structure. Due to its width, it is not yet decided if it will be a box-girder or not, but the principle itself is already decided.

Before concluding, we want to evoke the idea of constituting arch bridges with steel tubes filled with concrete. The idea evidently came from the design of the Val de Maupré Viaduct; but we consider that filling a pipe with concrete is mainly interesting when this pipe is always subjected to compressive forces, what logically leads to arches. These relatively light steel tubes could be erected in a first step, and then concreted. Perhaps temporary cables could remain during the concreting operation, so that a part of the arch self weight could pass in the concrete.

We worked on this idea with S.E.E.E. for

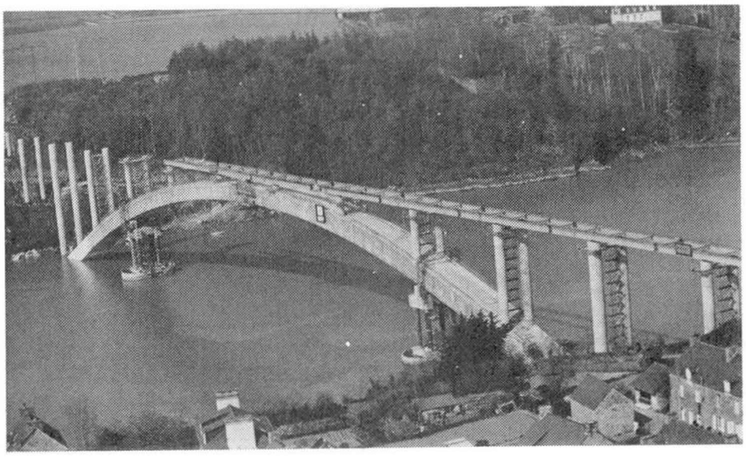

Figure 8: The bridge over the River Rance; the steel structure during erection
(photo G. Forquet)

Figure 9: The bridge over the River Rance; concreting the top slab
(photo G. Forquet)

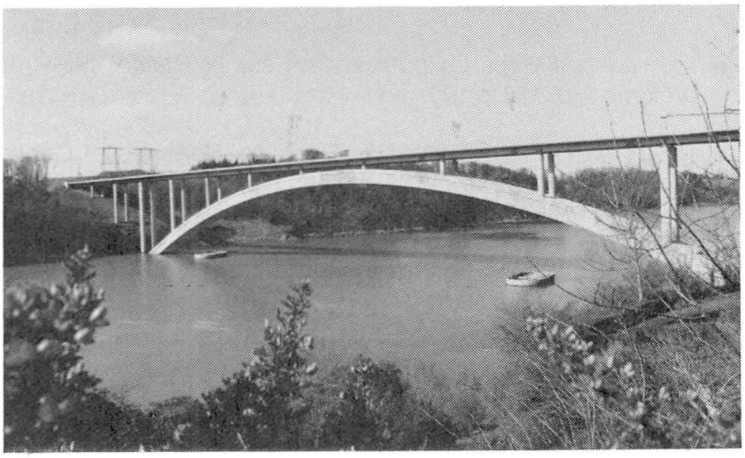

Figure 10: The bridge over the River Rance after completion
(photo G. Forquet)

the Tanus Bridge project, but the span would have been so large for an arch bridge – 360 m – that the size of the project and its cost excluded the solution.

We have developed a more practical solution for a project over the river Lot, at Villeneuve sur Lot: the arch was constituted of a single steel tube filled with concrete; but the arch was connected to the deck – a simple concrete slab, longitudinally ribbed – by two inclined webs, each made of a steel truss. René Walther already designed a small bridge following the same ideas. Unfortunately, our project was deemed too audacious and will not be built, despite the existence of the two other arch bridges in the city, one – famous – built by Eugène Freyssinet and the other of the 13th century.

5. CONCLUSION

We must remind some other special applications.

For example the steel frame incorporated in the Lanaye bridge, in Belgium: the design office – Greisch – proposed to build a light steel cable-stayed structure, made of two small I-shaped profiles; the concrete segments were built incorporating this structure, which helped carrying the shutters and the loads. But the great flexibility of the structure created more problems than the solution could solve.

We must, most of all, remind the use of steel elements as anchorage blocks: the steel anchorage elements embedded in the concrete heads of the Evripos Bridge pylons; but also the concrete elements embedded in the pylons of the Ben Ahin and Wandre bridges in Belgium, from which we drew our inspiration for the pylons of the Chalon Bridge...

Steel elements are also used, sometimes, for the lower anchorages in concrete decks, as in the Evripos Bridge according to Jorg Schlaich's ideas; or for carrying to the end-piers uplift reactions; or as struts in the cross-section, as in the Ben Ahin and Wandre bridges.

No revolution will come from all these ideas, but it is clear that engineers can find many solutions in the existing materials, techniques and technologies to built pleasant and efficient structures, on condition that their goal remains to drive forces in the best way, that is to say the most direct, the simplest. And it is also clear that there is no limit to their imagination.

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