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External Prestressing

Précontrainte extérieure

Äussere Vorspannung

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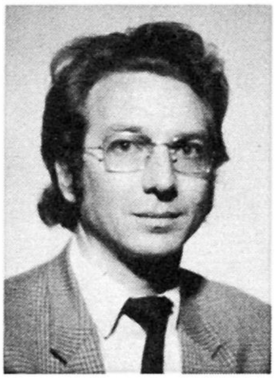

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SUMMARY

In this paper, the most recent structures erected using prestressing tendons outside the concrete are briefly described. Then the advantages of external prestressing are detailed, and the main techniques used or considered presently are described. Finally, the main difficulties of external prestressing procedures are pointed out, and attention is drawn to the problem of ultimate state design.

RÉSUMÉ

Cet article fait une rapide description des ouvrages récents construits à l'aide d'une précontrainte extérieure au béton. Il fait ensuite un bilan des avantages de la précontrainte extérieure et décrit les principales technologies utilisées ou envisagées. Il signale enfin les principales difficultés de la précontrainte extérieure et attire l'attention sur le problème du calcul à la rupture.

ZUSAMMENFASSUNG

Der Beitrag behandelt neuere Betonbauwerke, bei denen eine äussere Vorspannung angebracht wurde. Es werden eine Bilanz der Vorzüge der äusseren Vorspannung erstellt sowie die verwendeten oder in Betracht gezogenen Techniken beschrieben. Schliesslich werden die Hauptschwierigkeiten der äusseren Vorspannung und das Problem der Bruchbemessung aufgezeigt.

*Translated into English by Mrs. H. Virlogeux

In recent years, several bridges have been built with prestressing tendons placed outside the concrete. We think that the next few years, in which the design of structures is likely to evolve significantly, shall be marked by a generalized use of such external prestressing.

There is actually nothing new in the use of external prestressing tendons. Dischinger used them in the first two prestressed concrete bridges ever built, between 1928 and 1936. In France, around 1950, there are Villeneuve-Saint-Georges bridge, built by Lossier using cables as external prestressing, Vaux-sur-Seine and Port-à-Binson bridges, built by Coignet, and the bridge of Can Bia. Pr. Leonhardt, in the first bridge built by the incremental launching method, over Rio Caroni, used external prestressing tendons. Exterior prestressing was used for several years in the United Kingdom.

But it is only recently that, owing both to the development of very strong cables (from 19 to 37 T 13*) and to other technical advances, a new approach to external prestressing has led to simpler design and significant advantages. However, further technical progress is necessary, and may alter external prestressing methods very soon.

RESTORATION WORKS AND ERECTION OF CABLE-STAYED BRIDGES : THE LESSONS OF EXPERIENCE

Restoration and strengthening of existing bridges, as well as construction of cable-stayed prestressed concrete bridges, have contributed to the development of external prestressing techniques.

Repair work on certain bridges called for additional prestressing, which could only be placed outside the concrete. Using very strong cables, generally continuous over the whole structure length, was usually the solution to the difficult problem of cable anchorage, for which no provision was made in the original structure. Then the development of external prestressing technology started : type of duct, grouting procedure, etc.

Given the efficiency of external prestressing in such repairs, bridge designers systematically began to allow for subsequent installation of external strengthening tendons, should the need arise. The logical next step was the use of external prestressing in the initial design and construction phases.

Building prestressed concrete cable-stayed bridges also drew the attention of designers to the problems of cable replacement. Hence essential technological advances : anchorages allowing for tension adjustment, double-duct systems, and so on .

THE DESIGN OF EXTERNALLY PRESTRESSED BRIDGES

Wholly external prestressing tendons, continuous over each span

The first systematic applications of external prestressing were made by Jean Muller in the United States, in Long Key, Seven Mile, Channel Five and Niles Channel bridges of the Florida Keys. Precast segments are assembled using very strong cables (from 19 to 27 T 13). Each cable runs the length of

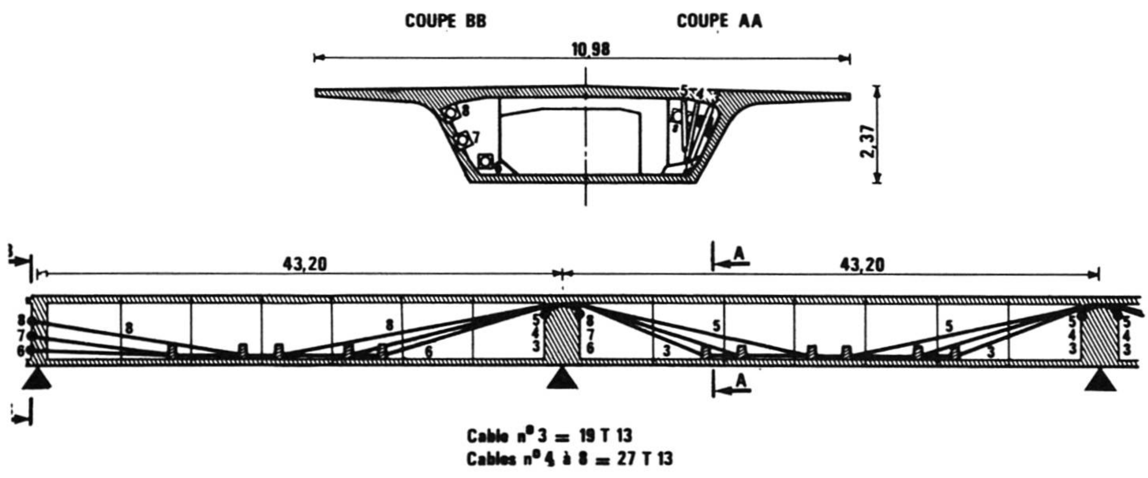


Figure 1 - Prestressing pattern of Seven Mile bridge

* Cables consisting of 19 to 37 strands, 13 mm in diameter.

one span, from pier to pier, and is anchored in the pier-supported segments. Each cable is independently shifted by small reinforced concrete separators placed at the connection of the web to the lower slab.

The same principles were applied in the Vallon des Fleurs and La Banquière viaducts, built by Campenon Bernard using the progressive placing method, with temporary cable staying. The prestressing cables are lighter (12 T 15), and separators are distributed over each single span. Apart from a few small construction tendons, the whole prestressing system is outside the concrete.

The cable pattern of the Bouygues company's Bubiyan bridge in Kuwait is quite similar. But the tendons pass under the deck along the span, and they are housed in a channel provided for it in each lengthwise rib of the lower slab; besides, instead of crossing each other in the pile-supported segment, the cables are systematically coupled.

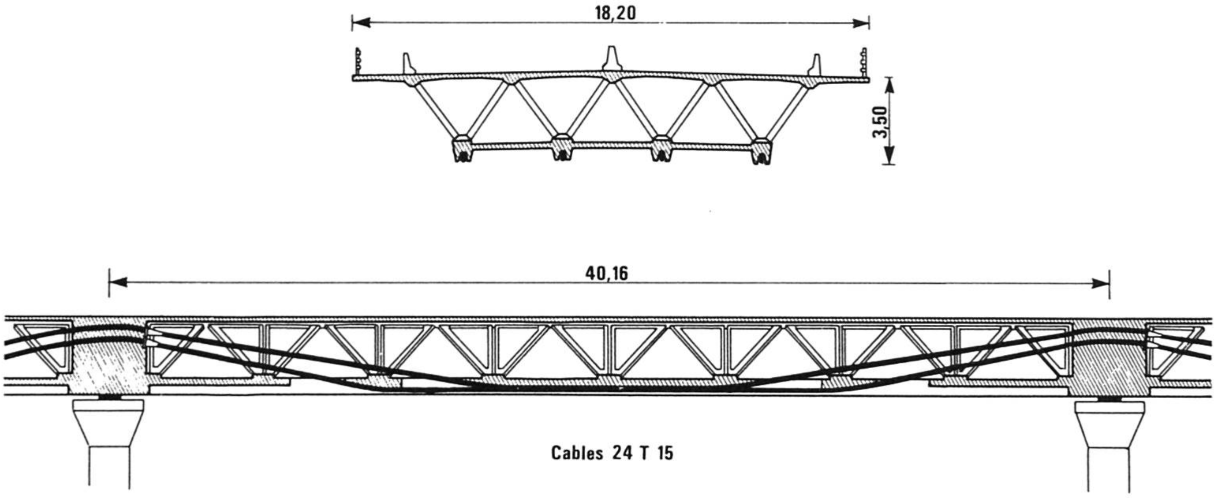


Figure 2 - Prestressing pattern of Bubiyan bridge

However, this type of prestressing can only be considered in bridges erected entire spans at a time : span by span on scaffolding, assembly of precast segments span by span on scaffolding, erection using temporary cable staying, etc.

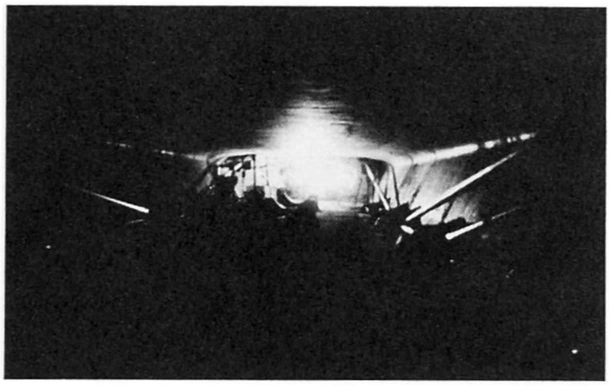
Wholly external, non-continuous prestressing

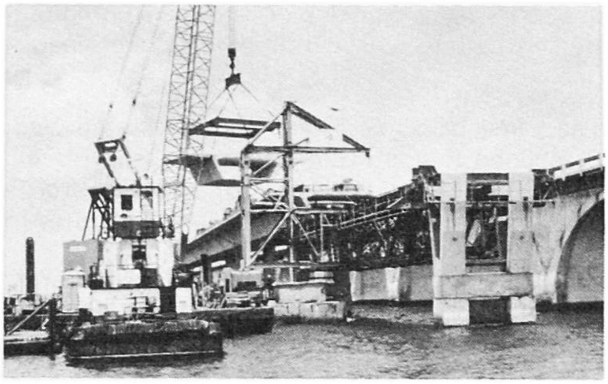
Externally prestressed structures may have more complicated cable patterns. An example is the viaduct of Sermenaz, built by Bouygues using the cantilever method. Here the conventional cable pattern consists in classical cantilever and closure tendons, all of them outside the concrete and anchored in vertical ribs provided in each segment.

But we think that the increased number of anchorages makes the works more difficult, and that these structures offer fewer advantages than those of the other two groups.

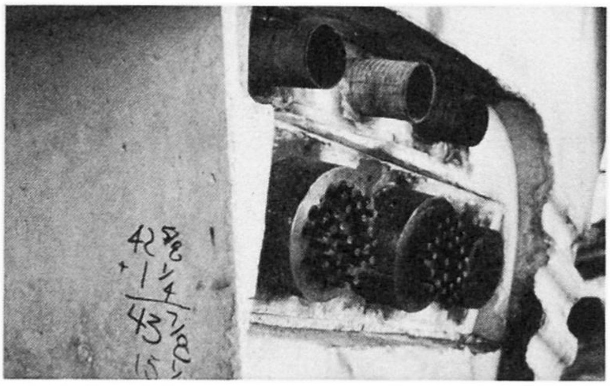
Mixed prestressing design

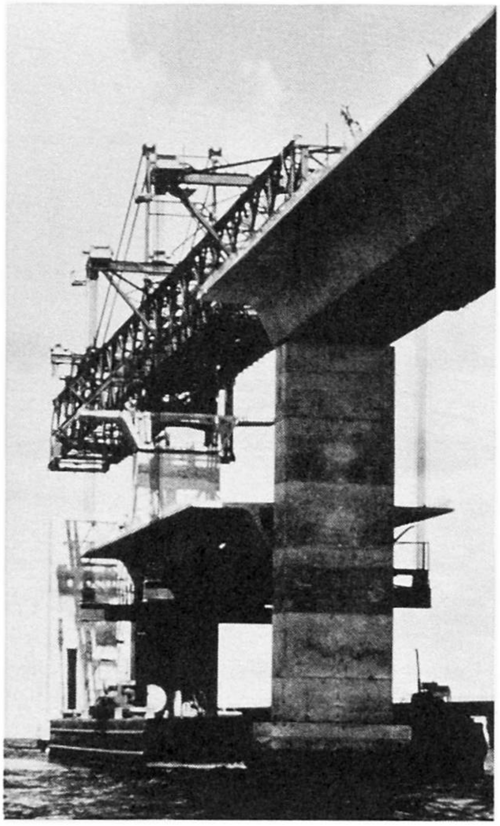
A different principle was devised by the S.E.T.R.A. for the La Flèche bridge, which was erected in two halves, one on each bank, on falsework parallel to the river, then rotated into their final position. Construction cables were so sized as to take over the bridge deadweight only; they were within the concrete. They were conventional, though horizontal, cantilever tendons, confined in the upper slab. After deck completion, very strong external cables (19 T 15) were used as continuous prestressing tendons, to balance all other loads. A few "internal" closure cables complement the prestressing process, which would otherwise be slightly undersized at the key or oversized at the piers.



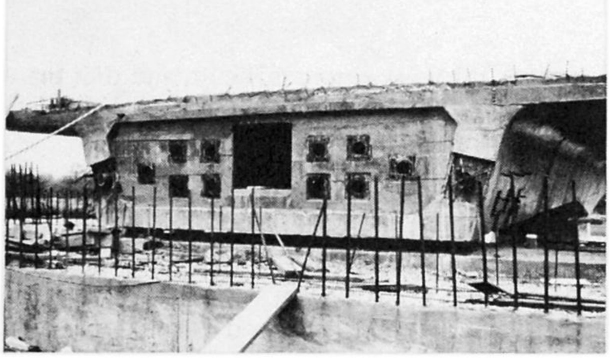


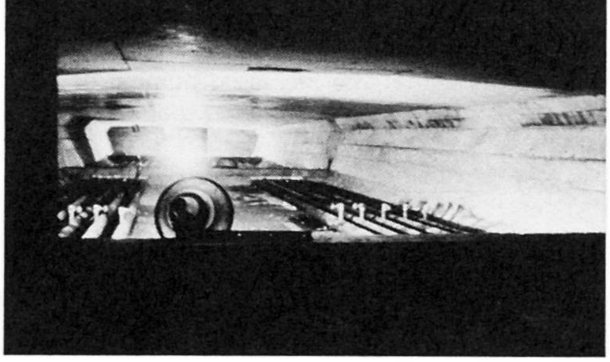
Long Key Bridge





Seven Mile Bridge





La Flèche Bridge

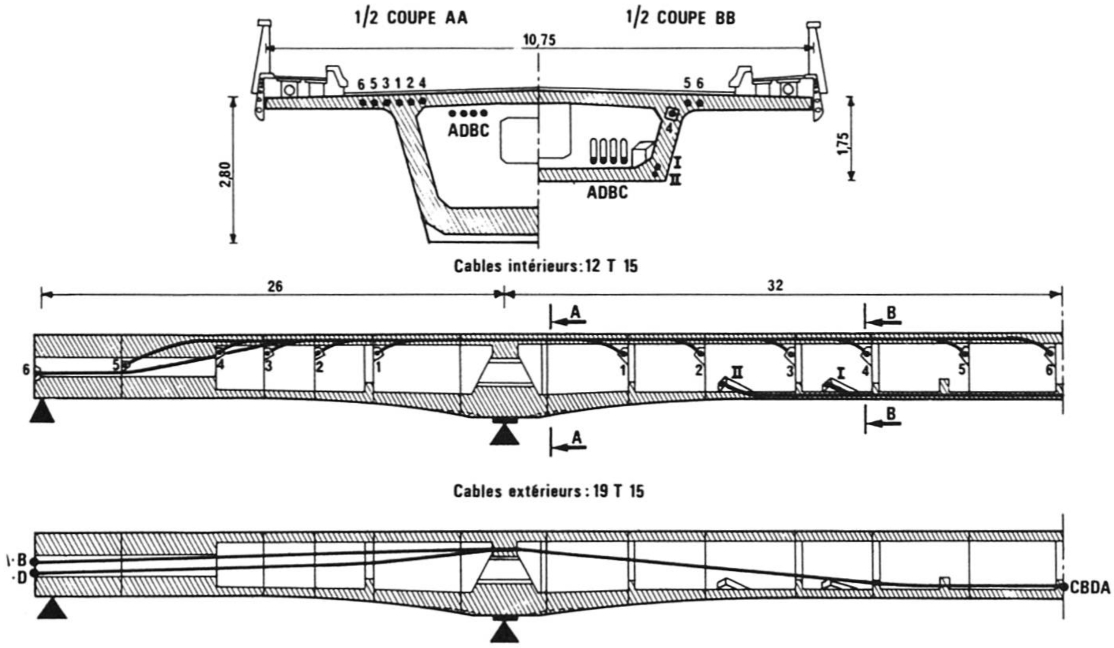


Figure 3 - Cable pattern of La Flèche bridge

The same principle was applied by the S.E.T.R.A. for the construction by the cantilever method of the Pont à Mousson viaduct, in which the external cables run the length of two spans, thus restricting temporary unbalances in the segments placed over the piers, due to anchoring forces.

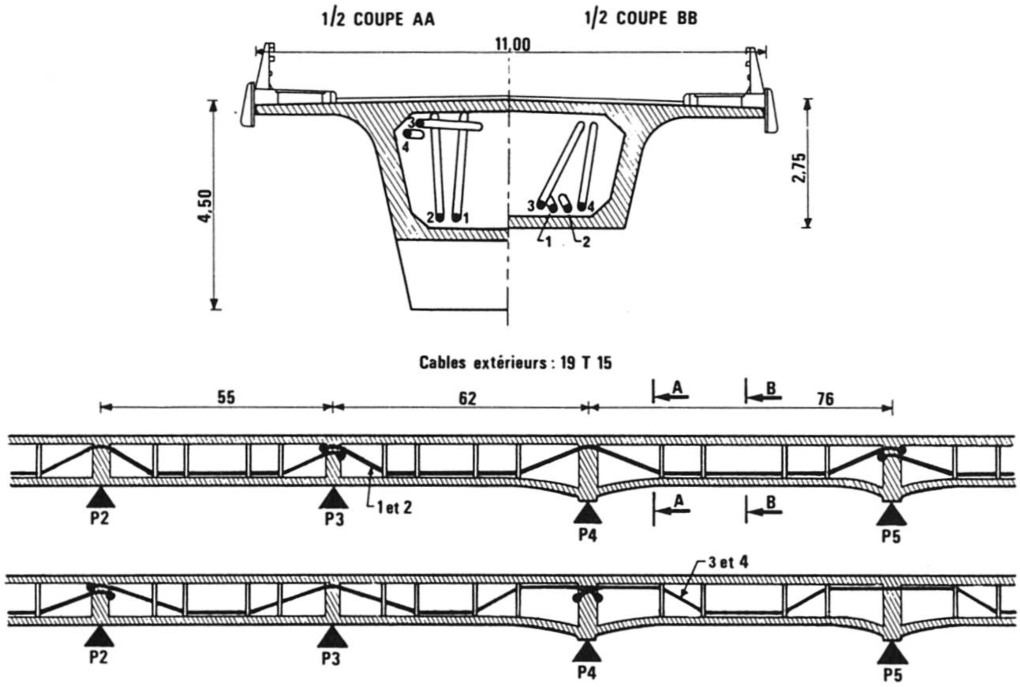


Figure 4 - Cable pattern of Pont-à-Mousson viaduct

Mixed prestressing design can be implemented using any erection mode, especially the incremental launching method. It is thus used in the bridge of Cergy, which is under construction by the Citra Company with a cable pattern similar to the La Flèche layout.

THE ADVANTAGES OF EXTERNAL PRESTRESSING

The advantages of external prestressing are many.

First of all, work time, a major economical concern for all companies, is reduced, by eliminating duct laying and adjustment operations; besides, placing the tendons outside the concrete results in a more streamlined layout, hence reducing friction losses, and thereby improving the efficiency of the prestressing system and the quality of the workmanship.

Concreting conditions also are improved by placing the tendons outside the webs, which can therefore be thinner, the deadweight of the structure being consequently reduced. Application of certain standards or regulations (French regulations, for instance), leads to increased effective thickness of the webs, since they are cable-free, and the thickness of the ducts is no longer deducted from web thickness. This yields a higher value for allowable shear force for a given thickness.

In the case of mixed prestressing design, as the number of cables embedded in concrete is greatly reduced, the gusset plates may be smaller, and the cable layout is simpler (hence reducing friction losses, and thereby improving their efficiency).

The injection procedure is obviously easier when the tendons are external : concrete cannot enter the ducts and obstruct them, it is easier to check the injection process, access to inadequately grouted areas is easy, etc.

Finally, with a careful external prestressing design, replacement of broken or corroded tendons is possible. No allowance was made for the replacement of external tendons in the Florida Keys bridges, or Bubiyan bridge, but such replacement will be easy in La Flèche, Pont à Mousson and Sermenaz bridges.

EXTERNAL PRESTRESSING TECHNOLOGY

Cables injected with cement grout in polyethylene ducts

In the first modern bridges with external tendons (the Keys bridges), prestressing tendons were placed in plastic ducts (high-density polyethylene), then injected with conventional cement grout. The problem is that this does not always allow for the replacement of tendons.

The following provisions are necessary in order to make the replacement of a tendon injected with cement group possible :

- whenever a tendon goes into the concrete, its path must be either straight, or circular, so that it can be taken out ;
- whenever a tendon goes into the concrete, a double-duct system must be provided, or a product intended to make extraction easier must have been placed over the duct (steel duct, heating-system-type, or plastic duct) ;
- the access to the anchorages must be easy, and the extraction of an anchorage must be possible from behind. In conventional anchorages, this is easy only when the layout at the anchorage is straight ; providing always for the double-duct system or the release agent.

Finally, when cutting external cables injected with cement grout, care must be taken regarding worker safety, and it must be done without transfering unallowable stresses to the often small-size separators.

Grease-injected tendons

Subsequently, the notion of grease injection was developed, based on the techniques used in nuclear reactor confinement buildings. Experience was acquired, here again, in repair works : temporary strengthening of the Tours bridge, strengthening of the Bayonne and Layrac bridges. The La Flèche bridge was erected using this procedure.

Grease is viscous at ambient temperature, it must be heated to 50 to 100° C, depending on its nature and on the cable length, before it may be injected. This accounts for the heating-system-type metal ducts selected for this type of job. But the need for completely watertight ducts raises problems of connection, since welding is difficult when the ducts are close to concrete.

The present trend would therefore be toward plastic ducts (high-density polyethylene), and greases with low viscosity at relatively low temperatures. The external tendons of the Vallon des Fleurs and La Banquière viaducts were thus injected in plastic ducts, with grease heated to about 50° C.

Galvanized cables

Galvanized cables can be left unprotected, but then tendon-holding devices must be provided at very short intervals, to prevent damage in case of a strand or cable breaking.

This solution has recently been used in the temporary strengthening of a viaduct. But the capacity of anchorage of the jaws was much reduced through an accumulation of zinc, due to the great tendon length, and two strands slackened suddenly.

This technique will be used in the Sermenaz viaduct.

Grease-protected, plastic-coated strands

A new notion consists of using cables made of grease-protected strands, individually coated with plastic (polyethylene). In this case, the cables must be kept within stiff plastic ducts, or, alternatively, numerous holding devices must be used to keep the cables in place, from a safety standpoint. Besides, the tendons must be specifically protected at anchorages, and this is no easy task.

The first application of this procedure, apart from repair jobs such as the covering shell of the transmitter of Feldsberg, will be the Saint Agnan viaduct, to be built by Campenon Bernard in 1983.

EXTERNAL PRESTRESSING : SPECIFIC PROBLEMS

The technique of external prestressing has specific problems.

First of these, the problem of tendon vibration. External tendons must be held in place at rather short intervals (about 10 m) in order to restrict vibrations and to prevent risks of resonance with the structure. For long spans, this may call for holding devices in the intervals between separators.

Another problem lies in the diffusion of prestressing forces.
On-pier cross-beams, which are used to anchor external tendons, are subjected to very important, though mostly temporary forces. Erection unbalances and diffusion forces are somewhat restricted by such cable patterns as those devised in the Pont à Mousson viaduct, or in the Saint Agnan viaduct, with a closely related pattern. Anyway, on-pier cross-beams must always be largely sized.

The prestressing force exerted at the abutments is much higher in the case of externally prestressed bridges than in conventional structures. Special attention must be given to the stability of the overhanging elements of the upper slab and of the slabs between the webs. We have provided for transversal prestressing at both ends in the La Flèche bridge and in practically all structures designed afterwards.

Finally, anchoring in an anchoring block is much more difficult in the case of an external tendon than in the case of a conventional internal tendon : whereas the prestressing force goes "into the material" in the case of conventional tendons, it is tangent and excentric in the case of external tendons.

Some engineers also feel insecure about the risks of fatigue of tendons on separators. It is obviously wise not to allow small bending radii (we must ask for at least 3 metres for 12 T 15 tendons, and more for very strong cables). Research in this field will be started very soon.

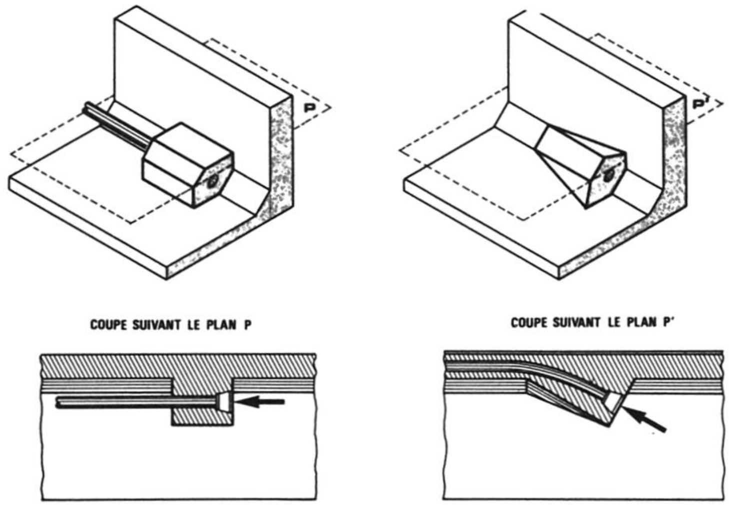


Figure 5 - A comparison of anchoring on an anchoring block with an external prestressing tendon and a conventional, internal tendon.

ULTIMATE STATE DESIGN

Still the major theoretical problem in the case of external prestressing is the problem of ultimate state design.

If we assume that the tendons do not slip over the separators (a very likely assumption, if the deviation angles are sharp enough), the tension variation of a tendon between two successive separators is given by its lengthening :

$$\Delta \ell = -\int_{x_i}^{x_{i+1}} (\delta u + e\delta w)\,dx$$

where :

δu denotes the average relative shortening of the typical section,
$\delta \omega$ denotes the differential rotation
and e denotes the tendon excentricity.

Whereas in the case of a tendon within concrete, the tension variation is in direct connection to the cross-section deformation :

$$\Delta \varepsilon_a = -(\delta u + e \delta \omega)$$

Load-induced stresses in prestressing tendons are therefore smaller in the case of external tendons, and depend on the overall deformability of the structure.

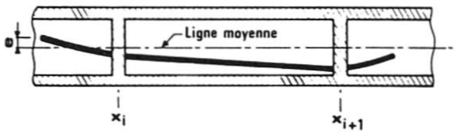


Figure 6 - External tendon over-stressing : calculation data

The ultimate moment of a cross-section, as defined by a given total deformation of prestressing tendons (10.10^{-3} in the French regulations), is almost similar in a cross-section with internal prestressing tendons and in a cross-section with prestressing tendons outside the concrete. However, it is lower in the case of a mixed prestressing system. But in the case of wholly external prestressing tendons, the displacements leading to maximum deformation of prestressing tendons are very important, and do not appear to be allowable, especially in the case of bridges made of prefabricated segments, without any passive reinforcement in the joints.

Before the complete results of research are known, we admit that the overstresses of external tendons may be neglected in ultimate state design, which are carried out with classical values of concrete deformations.

CONCLUSION

External prestressing makes the structure design and erection simpler, thus going the way of progress. Besides, the quality of the structures is improved, if only by making it possible to replace tendons with a few special provisions of negligible cost.

It is therefore most promising.

The concept of external prestressing will mainly evolve in function with the evolution of technology. But these are early days and future trends cannot be defined now, even though we may have a fair idea of what they will be.

Anyway, adequate means to deal with ultimate state design of externally prestressed structures are still to be developed.

Rotation of La Flèche bridge (first part)