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Evolution of Concrete Cable-Stayed Bridges

Evolution des ponts à haubans en béton

Die Entwicklung der Schrägseilbrücken aus Beton

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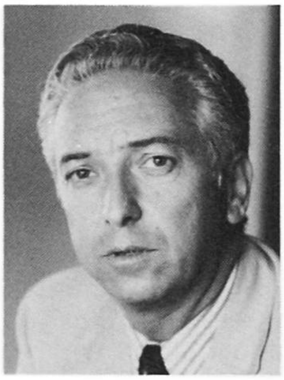

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SUMMARY

This paper briefly describes the evolution of concrete cable-stayed bridges during the last ten years, and points out the recent trends in the techniques of design and erection of these structures.

RÉSUMÉ

Cet article décrit rapidement l'évolution des ponts à haubans en béton au cours de la dernière décennie et indique quelles sont les tendances récentes dans la conception et la construction de ce type d'ouvrages.

ZUSAMMENFASSUNG

Der Artikel gibt eine kurze Beschreibung über die Entwicklung der Schrägseilbrücken aus Beton im Laufe des letzten Jahrzehnts. Er zeigt die neueren Tendenzen im Entwurf und Bau dieses Bauwerktypes.

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*Translated into English by Mrs. H. Virlogeux

1. THE THREE GENERATIONS OF CABLE-STAYED BRIDGES

During the last twenty-five years, concrete cable-stayed bridges have undergone a rapid development ; with three successive generations of structures.

First generation structures featured a limited number of cables spaced by several dozen meters, decks with high bending stiffness and extensive internal prestressing systems. In these structures, cables were used as substitutes when certain deck bearings could not be constructed.

Second generation structures consisted of bridges with many widely distributed cable stays, with partial suspension ; the deck rested on stiff bearings placed in the tower axis. These structures were a logical extension of traditional cantilever bridges, in which longitudinal cables placed outside the concrete acted as cable-stays and were supported by the piers which ensured their deviation.

Their decks, with medium bending stiffness, could be considered as beams resting on elastic bearings. They had two major avantages over first-generation structures :

- simpler force transfer both to the deck frame and to the pylons, due to the reduction of concentrated loads at anchorages and to reduced bending between suspension points.
- easier replacement of damaged cable-stays without traffic interruption, since the distribution of forces in the structure was not noticeably altered by the suppression of one cable.

The prototype of second-generation structures is the BROTONNE bridge, completed in 1977. The COATZACOALCOS bridge, presently in progress, is a replica of the BROTONNE bridge.

Finally, the third generation consists of bridges with many widely distributed cable stays, with continuous suspension. In these structures, the whole deck length is supported by cable-stays, the deck does not rest on the pylons. The behaviour of this type of structure is different from that of a bent beam.

The deck constitutes the compression flange of a triangulated system in which the cable stays are the tension diagonals and the pylon the compressed member. Thus the deck height, which is almost independent of the deck span, may be limited, provided that it resists buckling and its longitudinal deformations are consistent with the structure live loads.

The PASCO-KENNEWICK bridge, designed by Pr. LEONHARDT, was the first bridge of the third generation.

The last two structure generations have completely replaced first-generation structures.

2. CABLE STAYS AND ANCHORAGES : MAIN FEATURES

In the first bridges, cable stays consisted either of rods in prestressed concrete or of locked cables. Presently, prestressing tendons are used almost exclusively. They are made of parallel wires or strands, with better mechanical characteristics than locked cables : better defined elastic modulus, higher breaking strength. Furthermore, corrosion caused significant damage in locked cables of several structures, and their replacement, as well as their placing, were difficult, due to their large sockets.

Anti-corrosion protection of prestressing tendons is achieved by placing them within a watertight envelope and injecting anti-corrosion material, usually cement grout, into the inner space. The envelope may consist of metal ducts, either of paint-coated trade steel, or of stainless steel (5 mm thick,10 to 25 cm in diameter), connected by welding or by sleeves. Polyethylene ducts, resisting ultraviolet rays, have also been used. But wide cracks and abnormal deformations have appeared on some of these ducts, after several years, and evidenced alterations of the material, probably due to several reasons : winding and storage on coils for long periods, thermal stresses, grouting conditions, etc. Some care is therefore required when selecting this type of ducts.

Protecting cable-stays against fatigue begins with limiting their maximum working tension to 40 % of the breaking stress and their variation in tension under alternate loading to 20 kg/mm^2.

Fatigue is particularly noticeable in anchorage areas.

There are two types of cable-stay anchorages :

- high-am anchorages (with high amplitude as regards fatigue). The wires are "buttoned" to a plate within a cone-shaped anchorage filled with steel balls and epoxy resin.
- heavy-duty prestressing anchorages derived from traditional anchorages, with anchor plates and jaws to anchor each single strand separately.

Scale models of the anchorages must be tested in order to ascertain that their fatigue strength is 2×10^6 cycles when subjected to cable-stay working loads.

Being subject to wind effects, cable-stays may undergo vibratory phenomena which can lead to fatigue failure. However, this can be remedied by using damping devices.

Now the best prevention against corrosion and fatigue consists in replacing incidentally damaged cable stays, which gives usually the corollary possibility of adjuting them, both on erection and in use.

3. SUSPENSION

The suspension of cable stayed bridges is of great economical importance, since cables cost generally about one third of the total cost of the bridge.

3.1 Longitudinal cable arrangement

In the longitudinal direction of the bridge, there are three major cable configurations.

a) Harp systems, wherein the cables are parallel.

This configuration reduces the risk of elastic instability of towers, because the points of intersection are evenly distributed along the tower height, and it leads to design simplification, due to the constant angle of incidence of the stays. On the other hand, bending stresses induced by the cable-stays in the towers are considerable, as are compressive stresses in the deck.

This is the most attractive double-plane cable system from the aesthetic viewpoint, because all the cables are parallel, from whatever angle they are viewed.

b) Radiating systems, wherein the cables converge at a single point of the top of the tower.

But this configuration can hardly be achieved because of the size of stay anchorages, which must be easily replaced in case of damage. It is usually thought preferable to have cables emanating from the top of the tower with equal spacings : this is the fan-type arrangement.

Economic comparison of these two types shows that radiating systems require lesser weights of cable steel than harp systems, when the ratio of tower height above the deck to center span length is under 0.30. When this ratio is 0.20, the gain is around 15 %. Though the weight of cable steel in harp arrangements with tower height/center span length ratios over 0.40 is found to yield a 20 % gain over the above 0.20 ratio, the problems raised by the wind resistance and elastic stability of high towers are difficult and notably increase the costs.

However, when the center span is not very long ($L < 200$ m), a high tower with harp-arranged cable stays is probably the most economical solution.

In all other cases, when the ratio of tower height above the deck to center span length ranges from 0.15 to 0.25, radiating configurations are usually preferred.

3.2 Transverse cable arrangement

In the transverse direction, cables may lie either in a single plane in the longitudinal axis of the bridge (axial suspension), or in a double plane, with two parallel or converging lateral planes (lateral suspension).

Axial suspension systems are normally used in bridges with two-way traffic lanes separated by a median strip in which cables can be housed. The motorist can enjoy an unobstructed view of the exterior, but these systems require increased torsional deck stiffness. They are therefore more adequate for bridges with medium width (< 24 m).

Heavy vehicles induce limited stress variations in the cables, since they usually travel on the "slow" lanes, the furthest from the cable plane, and the torsional stiffness of the deck ensures a good distribution of corresponding stresses into several cables.

In lateral suspension systems, the aerodynamic stability of the deck is improved because the transverse cable-stay arrangement increases its torsional stiffness. But it is still better when pylons are inverted V- or inverted Y-shaped, because this configuration prevents different longitudinal movements of the anchorages of the two planes.

Torsion stresses in the deck are low because excentered loads are directly transferred to the cable stays. Conversely, stress variations in the cables are high, because heavy vehicles move close by the cables.

Lateral suspension systems are most adequate in wide structures of the 3rd generation (width > 24 m), in which it is difficult to obtain both low bending stiffness and high torsional rigidity.

3.3 Towers

In the longitudinal direction, a tower (or pylon) generally consists of a single vertical element whose resistance to horizontal load-induced forces is mainly ensured by the cable stays.

Its longitudinal rigidity depends both on the cable-stay configuration and on the bending stiffness of the deck.

The transverse design of tower closely depends on the nature of suspension (axial or lateral type) ; several forms are possible :

- one or two individual cantilever pylons (Fig. a1 and b1). This is aesthetically the simplest, and economically the best solution, whenever the pylon strength and elastic stability can be ensured transversally. Though most elegant in the case of a single central pylon, it then requires oversizing of the deck. But it must not be used in seismic areas.

- two vertical columns joined at the top by a cross member (Fig. b2). This is an adaptation of the above solution, where the pylon is very high and cable planes are slightly inclined.

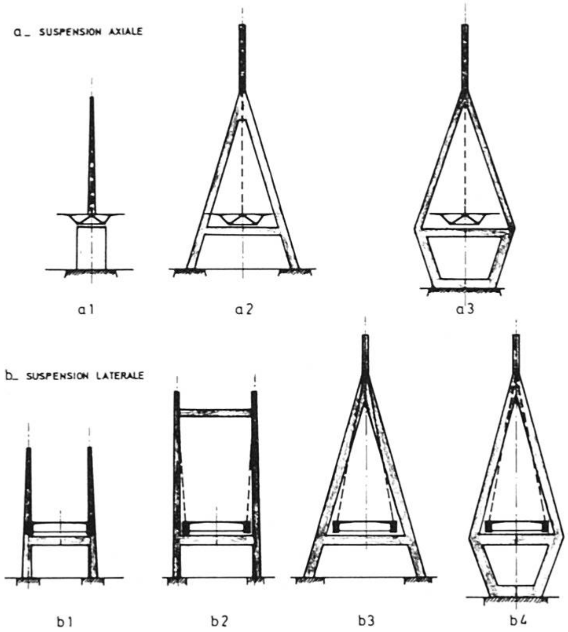

Figure 1 - Different shapes for towers

- inverted V or Y frames, quite adequate for long span structures. If large clearance is needed under the deck, the frame legs are joined under the deck by a cross member, in order to reduce the foundation volume (project for the Rio Caroni bridge). The lower part of the tower may also be shaped as a single shaft bearing both Y legs (COATZACOALCOS bridge).

3.4 Connection of cable stays to towers

Several solutions have been proposed for the difficult problem of cable-stay connection to towers (Fig. 2).

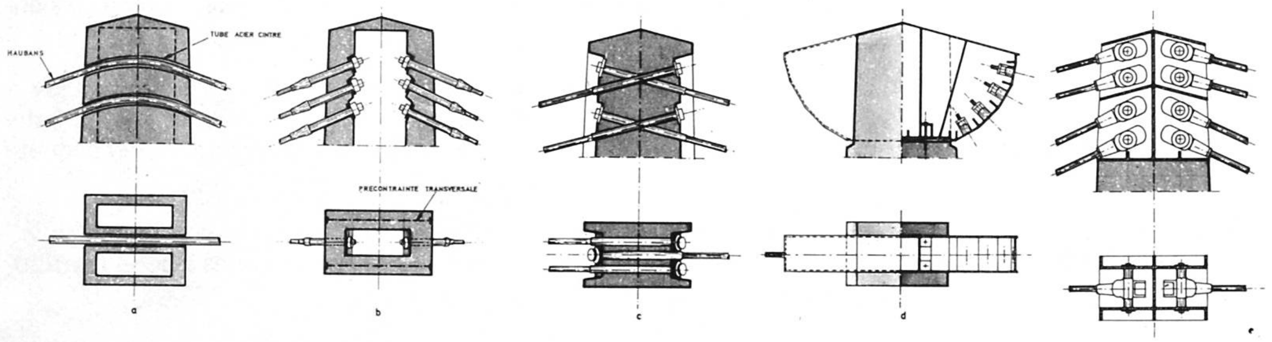

Figure 2 - Connection of cable stays to towers

A new solution, both economical and space-saving when the cable stay tension is similar on either side of the tower, has been applied in the BROTONNE bridge (Fig. 2.a) : the cable stays pass through the tower within embedded steel pipes. Lately, at the design stage of the COATZACOALCOS bridge, the fatigue behaviour of cables above the curve, which was thus far ill-known, has been tested at the Laboratoire Fédéral of the EMPA in Switzerland. A 12 T 15 cable, anchored to fixed blocks at both ends and injected, was tested in conditions similar to the project (radius of curvature = 2.25 m, casing pipe, transition pipe). No strand broke under 2.10^6 cycles, with a stress variation of 15 kg/mm^2 and a maximum 75 kg/mm^2 stress.

This test, which simulated both the actual tension variations and angular deviations in the cable stays, was more severe than the conventional nonuniform ("undulated") tensile test procedures usually applied to end anchorage of cable stays.

In the POSADAS-ENCARNACTION bridge, cable stays are anchored within a space in the tower (Fig. 2.b). This solution required longitudinal prestressing bar to take over tensile stresses resulting from opposite anchorage actions, thus re-establishing, so to speak, the continuity of cable stays. This arrangement is both costly and space-consuming.

Cable-stay intersection with anchorages at the outside faces of the towers is possible when cable stays may be arranged to prevent torsion stresses in the tower : for instance, in the case of asymmetrical planes, with different numbers of cables on either side of the tower (see Fig. 2.c).

Cable-stay anchorage to a steel piece at the tower top requires design provisions which are complicated, often unsatisfactory, as regards steel work, and generally expensive. This method has been applied in the PASCO-KENNEWICK bridge (Fig. 2.d and 2.e).

4. TRANSVERSE STRUCTURES

The transverse structures of cable-stayed bridges must comply with a number of often contradictory requirements : lightness, aerodynamic stability, ease of cable-stay anchorage.

The design of the transverse structure is different according to the deck suspension system : axial or lateral suspension.

4.1 In axial suspension bridges, the transverse structure must have high torsional rigidity in order to resist asymmetrical loads. Cable stays are then anchored either close to the web planes, or above the connection nodes of the elements which constitute the transverse section arranged as a triangulated system.

Axial suspension systems call for deck oversizing, in order to accommodate the cable-stays in the median strip and protect them against vehicles.

There are two types of structures :

- 3- or 4-web box-girders,
- 2-web box girders, with interior triangulation.

4.1.1 3- or 4-web box-girders

Three-web or box-girders have two main disadvantages : difficult access to cable-stay anchorages, usually placed under the center web (Fig. 3.a), and cross sectional deformability, due to the transfer of suspension forces from the cable-stays to the lateral webs.

The first disadvantage can be remedied either by a double-plane axial cable-stay configuration (Fig. 3.b), or by splitting the central web (Fig. 3.c), thus obtaining a four-web box-girder.

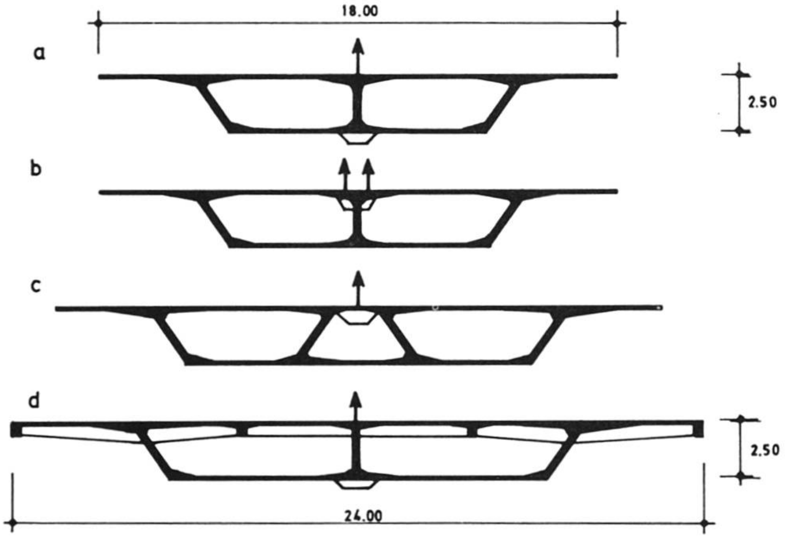

Figure 3 - Multicell box girders

Cross-sectional deformability does not appear until the deck width exceeds 20 m ; it can be reduced by cross-stiffeners (Fig. 3.d), sometimes associated with longitudinal stiffeners.

4.1.2 2-web triangulated box-girders

Two-web triangulated box-girders are generally lighter than the other systems, and cable-stay tensioning, systematically made from within the deck, is much easier.

Several configurations are possible, depending on the deck width :

- triangulated box-girder with two inclined webs, with inclined struts as interior stiffening (Fig. 4.a) : BROTONNE and COATZACOALCOS bridges ;
- triangulated box-girders with two inned webs and interior stiffening provided by inclined struts and vertical columns (Fig. 4.b) : project for the OTTMARSHEIM bridge ;
- triangulated box-girder with two vertical webs, inclined struts as interior stiffening and exterior bracings to support overhanging parts (Fig. 4.c) : project for the ELBEUF bridge ;
- triangulated box-girder with two inclined webs, with inclined struts as interior stiffening, and cross stiffeners on the top and bottom slabs.

4.2 In the case of lateral suspension systems, the structure sometimes consists of multiple-web triangulated box-girders (Fig. 5.a). Interior diagonals are desirable, in order to help retaining the cross-section shape.

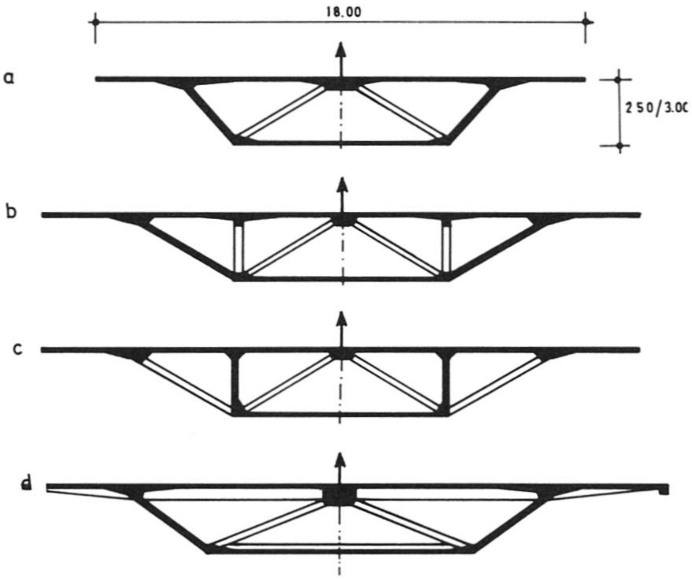

Figure 4 - Two-web box girders

However, the transverse structure may be simpler, without torsional rigidity. Then it consists of two main beams, placed under the cable-stay planes, connected by the upper slab and by cross-stiffeners spaced by 3 to 5 m.

Edge beams are box-girders (Fig. 5.b), as in the PASCO-KENNEWICK bridge, or solid beams (Fig. 5.c). Thus the anchorages of cable stays are independent of the stiffeners.

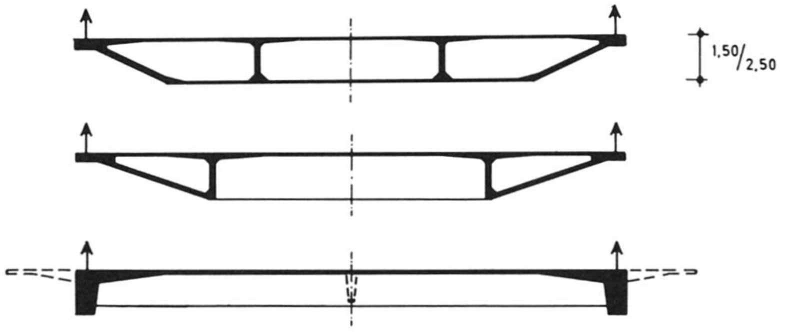

Figure 5 - Lateral suspension structures

An additional longitudinal beam is sometimes useful to ensure a proper distribution of concentrated loadings between the various cross-stiffeners.

Being identical, cross-stiffeners may be easily precast and assembled to edge beams by prestressing.

They may also be solid or triangulated beams. In this type of structures, with lighter deck deadweight, longitudinal stresses apply to the concrete section only, and the transversal strength of the structure is ensured by steel cross-stiffeners which, together with the upper slab, constitute a mixed cross-section.

5. A NEW SOLUTION FOR LATERAL SUSPENSION BRIDGES : THE UMBRELLA CONFIGURATION

The analysis of suspension problems in cable-stayed bridges has led us to the conclusion that one of the simplest and most economical configurations is a single-column tower, with continuous cable stays through the tower top.

This solution has been applied to an axial-suspension bridge, the Brotonne bridge. However, in this case, the tower must be oversized to prevent lateral buckling.

The extension of this idea to lateral-suspension bridges - to which it has never been applied - leads to a new cable-stay configuration : the "umbrella" cable-stay arrangement, which offers several advantages :

- simpler design of the tower bottom and foundation, due to the direct transfer of the vertical loads of the tower,
- reduction of the risk of tower buckling, because the cable stays behave as longitudinal and transverse bracings,
- suppression of the transverse cable-stay thrust, perpendicular to the tower top, due to the cable-stay continuity,
- finally, in the case of total suspension bridges, the deck is blocked horizontally because it rests directly on the tower which crosses it.

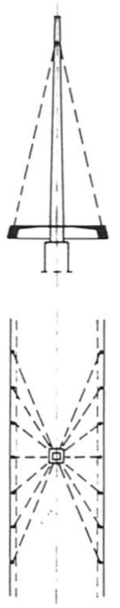

Figure 6

On the other hand, umbrella cable-stay arrangements require oversizing of the deck width to accommodate the tower volume (though axial suspension towers have still greater volumes, and are more sensitive to buckling). An attractive solution, for wide decks (> 30 m approx.), consists of distributing cable-stays among three planes, since the median strip, widened due to the presence of the towers, allows for economical anchorage of the medium-plane stays. Thus the deck deadweight is reduced while its transverse strength is ensured.

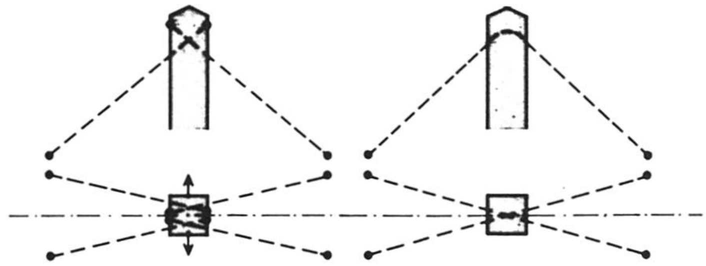

Figure 7

These new notions are applied in an alternative design solution for the bridge of GENNEVILLIERS avenue, featuring a total lateral suspension of a 30-m wide deck and a fan configuration.

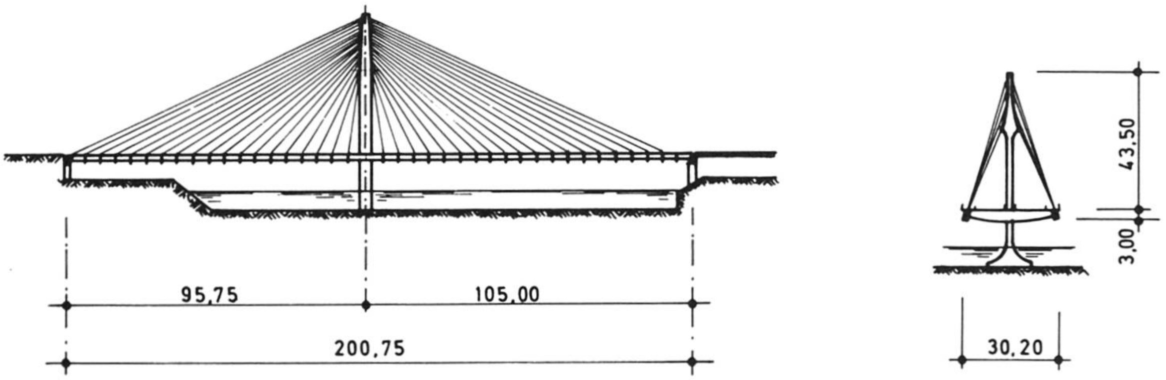

Figure 8 - Gennevilliers project

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