An innovative composite structure: the viaduct crossing the Marne valley in Meaux

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1. "South-west skirting of Meaux" operation

Situated in a privileged setting on a loop of the Marne river, 40 kilometers east of Paris, Meaux, sub-prefecture of the Seine et Marne department has been a significant economic center since antiquity. Even today, several heavily used truck (lorry) routes converge in the center of Meaux : the RN 3 from west to east, the RN 330 in the northwest, and the RN36 in the south, resulting inevitably in heavy traffic during peak hours.

To decrease traffic in the center of *Meaux*, a large-scale by-pass project between RN 36 in the south and RN 3 in the east skirting the metropolitan area on the west was approved with 4 co-financiers (the State, the *Ile-de-France* Region, the Department, and the city of *Meaux*. The construction of this skirting is included in the 10^{th} and 12^{th} *Contrats de Plan Etat-Région* and should be completed in 2004. It is estimated that completion of this project will decrease in town traffic by some 3000 vehicles during peak hours, reducing air and noise pollution and increasing safety of drivers and residents.

The southwest skirting of *Meaux* is the section of this by-pass that is under State control. It's a 2x2 lanes motorway section, expandable to 2x3 lanes, 6 kilometers long, connecting A140 motorway in the south of *Meaux* near *Quincy Voisin* to the RD 5 near *Villenoy* on the west bank of the *Marne*.

The southwest skirting of *Meaux* is on the schedule of the "*Schéma Directeur de la Région Ile de France*" (SDRIF) to be a section of the future fourth ring road of *Ile de France*, connecting, in the long term, the A1, A4, A5, and A6 motorways.

This project has been state-approved on January 28, 1999. The total cost of this project has been estimated to be 130 million euros (30% State, 70 % Ile-de France Region)

2. The viaduct over the Marne valley

The layout of the southwest Meaux bypass leads off the A140 motorway to the west, north of Quincy-Voisins, and is cut deeply into the hill. South of Mareuil-lés-Meaux, it crosses an enormous natural breach, the Marne valley, downstream of the city of Meaux.

The chosen solution for this bridge was to construct an extraordinary and spectacular project: a 1,200 m long viaduct whose plane layout is a circle having an arc with a radius of 1,000 m, sloping 2.03% from east to west. Successively, from east to west, this viaduct will cross CV4 south of Mareuil-lés-Meaux, the Meaux Canal at Chalifert, the Marne, the Paris-Strasbourg train line and the Canal de l'Ourcq. At the tallest piles, the motorway platform will be approximately 30 meters above the valley floor. The east pier of this viaduct will be supported by backfill on the slope of the Nolonques hill at Mareuil-lés-Meaux and the west pier on the west bank of the Canal de l'Ourcq, at the middle of the Béghin Say de Villenoy sugar refinery decanting basin.

The preliminary study for this non-current bridge, constructed jointly by SETRA, DRE Ile-de-France and DDE de Seine-de-Marne, was approved by the Ministry decision of 17 July 1998. For the subsequent survey, it was decided to waive the circular of May 5, 1994, defining the conditions of elaboration, processing and approval of investment operations into the non-assigned national road network.

3. Within the "innovation charter", a performance-based invitation

3.1. Motivation of the procedure

The *Meaux* viaduct was chosen for its size, its geometrical characteristics, the natural quality of the site it crosses and the suitability of its design schedule with the launching of a performance-based call for tenders. At the proposal of the *Service d'Etudes Techniques des Routes et Autoroutes* (SETRA), the Roads Director decided to enter the construction of the *Meaux* viaduct into an innovation process, promoted as a partnership with public works building companies as part of the "Bridges Innovation Charter".

The SETRA proposal underscored the importance of maintaining company innovation capacities and the difficulty of expressing them in a conventional call for bids. As an example, the performance-based approach used by *La Société des Autoroutes du Nord et de l'Est de la France* (SANEF) resulted in the use of innovative techniques for the two viaducts on the A16 motorway.

The characteristics of the *Meaux* viaduct make it particularly interesting for innovative techniques (large bridge requiring a thorough architectural approach, but within which many choices are open regarding the engineering technique).

In conformity with Article 99 of the former Public Contracts Code, for technical grounds, bidding was initiated on the basis of a detailed functional program with the companies required to propose a project addressing the requirements of this program. The integration of the approach regarding innovative development meant that it was taken into consideration as one of the criteria of the judgment made.

The call for tenders also involved the establishing of the project and its engineering in conformity with paragraph 2 of article 99.

However, the call for tenders concerned only part of the design of the bridge because La Direction Départementale de l'Equipement (DDE), assisted by SETRA, La Direction Régionale de l'Equipement Ile-de-France (DREIF) and Le Laboratoire Régional de l'Est Parisien (LREP), prior to the call for tenders, had already drawn up a preliminary survey of the work, the studies needed for elaborating the functional program as well as the two technical reference solutions attached to the company tender documents. In addition, DDE will be ensuring the prime contracting of the project and handling the management of work performance (SETRA and DREIF will assist in checking the engineering and methods surveys, LREP for checking the quality of the materials implemented) so that the tender would result in a regular work contract.

That is why the establishing of the surveys by the consulted companies was only partial, since the performance-based call for tenders procedure was implemented as part of the general framework of article 99 of the Public Contracts Code and not in the particular framework of article 100 of the Public Contracts Code relative to design-engineering contracts.

A choice of procedure was implemented by the ministerial decision of July 17, 1998 which approved the *Meaux* viaduct EPOA (calls for tender procedure).

3.2. Call for tender criteria

The criteria under which the proposals were evaluated, in decreasing order, were:

- The technical quality of the terminated bridge
- Suitability regarding functional program, Durability, Safety offered by sizing, Innovative nature

- Aesthetic standard of the bridge and consideration for the site from the architectural and landscape standpoints
- Prices
- Specific production provisions:
- Production quality, Safety of workers and users of the tracks crossed, Reduction of effects on the environment
- Cost of maintenance and use
- Lead time

3.3. Criteria evaluation mode

The eliminating criterion was compliance with the functional program It defined the general data comprising the lengthwise profile, gauges and the various difficulties of the site (networks, use of channels and SNCF track). All the proposals complied with these requirements with a few minor exceptions and were corrected in the second bid.

To evaluate the technical standard of the bids, a team made up from SETRA and DREIF personnel analyzed each bid in its slightest detail.

On the one hand, regarding the general design, each project was examined in detail for its pertinence: validity of general design and construction methods (extension, balancing, general flexing of decks, supports, deep foundations, equipment).

Critical analysis of production methods to ensure production quality, safety of workers and users of the tracks crossed in the course of the works and reduction of effects upon the environment (access, engineering methods, excavation work).

Conformity with the functional program, especially concerning the geometry: layout, lengthwise profile, gauges, compliance with pier locations (within the strip provided for) and the easements of access backfill, functional widths, etc.

Verification of calculation, then sizing hypotheses (constructional calculation and provision data) during the construction phases and in service.

Further, design details were put through thorough inspection (assemblies, bosses, bracing, etc.). The latter point was checked in particular when the solution or its construction mode involved any innovation (conflicting calculations were carried out when it was deemed necessary).

Once the general design and sizing had been tested, the following points were checked in greater detail.

Drawings of supports and deck, in particular assembly design.

Validation of the construction provisions: access, site installations, earthworks (right of way), dumping, hygiene and safety, environmental friendliness.

Validation of load transfers, then checking the sizing of the foundations.

Validation of the pre-survey and the essential elements of the CCTP specification, the engineering schedule and the price content.

To grade the aesthetic standards of the projects, an architect and a landscaper used the plates required in the proposal, comprising architectural renderings and insertion into the landscape against photographs supplied in the DCE documents. In addition, the architects for each project were required to submit a memo explaining their choices and the reasons that led them to choose the various architectural aspects of the structure.

Finally, to estimate the price criterion, placed in third position only, the DDE authorities checked the pre-surveys supplied with the bids and possibly integrated the quantities to be added subsequent to technical analysis (addition of prestressing, reinforcement) or omissions.

4. Proposed solution: A composite prestressed concrete structure with "plano-tubulaires" webs

The bridge structure consists of a single prestressed concrete continuous beam having a total length of 1200 m between the centers of the outer piers. This continuous beam, having a constant height of 4.50 m, has a transversal section consisting of a 31.10 m effective width tubular mono-caisson.

The transversal section of this deck consists of an upper slab supporting the road course and a lower slab, both of concrete with two vertical metal webs of original design known as "plano-tubulaires webs®" and four diagonal inner and outer braces designed to support the upper slab and, at the same time, provide the counter-bracing of the structure by making it particularly rigid. These braces, the inner ones of concrete and the outer ones of metal, are W shaped and arranged in planes perpendicular to the center line of the bridge, every 3.105 m.

The deck consists of 22 spans of slightly variable lengths because of the demands of the positions on the ground, but included between 49 and 59 m, except for the span over the Marne which is 39 m, and the span on the east bank which is 34 m.

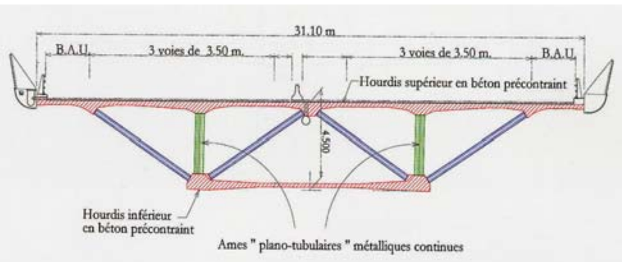
The plane axis of the bridge is a circle having a radius of 1,000 m and its lengthwise profile is a straight line on a constant slope.

The deck is prefabricated in successive sections and pushed into place.

4.1. Transversal deck section

The transversal deck section consists of a rectangular central caisson with two vertical cores having a width of 12.50 m between cores, connecting the two slabs and braced almost continuously on the inside by diagonal stays arranged to form inverted Vees. The inner stays of concrete are connected to the slabs by reinforcement in readiness, while the outer metal stays are connected by plates fitted with studs.

In addition, the section includes, either side of the central caisson, wide lateral corbel sections supported every 3.105 m by external braces.



Over the 31.10 m effective width, the upper slab has a constant slope of 2.5% corresponding to the general camber of the deck. The thickness varies from 22 cm in the basic parts to 60 cm near the cores, 70 cm near the inner stays and 72 cm near the outer stays, with straight connecting gussets. It is also reinforced at its side ends by a thicker section of 25 cm over 45 cm width and over the entire length of the deck, for anchoring the transversal prestress cable and taking up the anchor forces of the BN4 barrier posts.

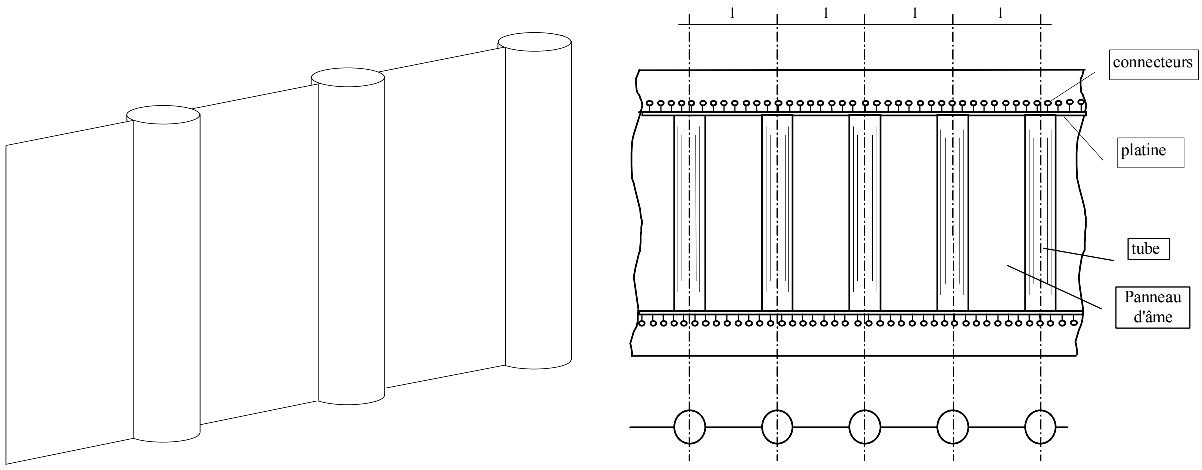
It is prestressed transversally by cables 4 T 15 S comprising 1860 MPa class lengths arranged every meter.

The lower slab, 13.0 m wide, includes two 1.30 m wide heel sections centered under the cores, connected by a slab varying in thickness from 20 cm at the center to 50 cm at the end of the straight connecting gussets. The side heels have an underside with a horizontal surface so as to develop longitudinally along the lengthwise profile of the bridge, forming a helix, thus pushing the structure.

4.2. The "plano-tubulaires" webs

The "plano-tubulaires webs®", protected by patent, consist of a section of 1.05 m long and 3.06 m high plane sheet metal panels, between 20 and 25 mm thick depending on their position in the structure, connected together by 508 mm diameter metal tubes, 12.7 mm thick with a vertical axis. These mixed panels (plane sheet metal/tube), at the top, have sheet metal plates for connecting to the concrete slabs by means of stud connections. The connection of these cores to the concrete of the lower slabs will be by direct interpenetration of the core into the node with horizontal studs.

The *plano tubulaire* web panel sections, sheet metal, tubes and plates, are of steel grade S355. All the metal parts of the structure are protected from corrosion by a triple complex of epoxy paint (draw 2).



Design in principle of "plano-tubulaires" webs

The top and bottom connections of the tubes and plane panels ensure uniform distribution of the shearing stresses through the entire height of the panel.

The vertical tubes are arranged every 1.55 m. Their radial deformability, by ovalizing, makes it possible to absorb without any opposition, and therefore without any force, the longitudinal deformations imposed upon or subjected by the concrete, resulting from prestressing or from thermal variations, shrinkage or creepage.

Accordingly, the prestress forces pass essentially through the concrete slabs, increasing their efficiency, and in addition, through a concentration of the material establishing inertia at the high and low points of the section, giving the latter a particularly high mechanical yield.

Among the other advantages resulting from the design of these cores, the presence of vertical tubes at regular intervals is noteworthy, offering natural stiffening of the core panel and overcoming the effect of classical vertical stiffeners.

Similarly, these tubes endow the core panel with some transversal rigidity so that it is possible to inset, at least partially, the lower slab to work together with the caisson structure.

A structure like this, in addition to being substantially lighter than a classical concrete structure, reduces the amount of prestressing needed while improving the performance of the concrete and steel working essentially in their preferred field of operation.

4.3. Longitudinal prestressing

The longitudinal prestressing of the deck consists of three cable families :

- first phase cables implemented before the structure is pushed into place, gradually as the successive sections of the deck are constructed:
- implementation second phase cables, used after the pushing of the structure, with the deck in its final position.

The first family cables are type 12T15S, class 1860 MPa, inside the concrete, arranged in the upper slab and lower slab, having a more or less straight path. In the current section, this family includes twenty cables running over the entire length of the structure, twelve in the upper slab and eight in the lower slab. At the front of the pushing deck, in the area perturbed by the console and the nose, the first phase prestressing is reinforced by raising the number of cables to 32 including twenty in the upper slab and twelve in the lower slab. The cables of the upper slab in the current section are set out in the five horizontal ribs located in the center line of the central caisson, near the cores and in the side corbels near the bearing points of the external stays. This arrangement of the cables in the five beams ensures accurate distribution of prestressing over the entire width of the slab and particularly good distribution of the applied forces. The eight cables of the lower slab are placed in the lower nodes under the plane-tubular cores with four cables in each node. The cables of the upper slabs are coupled with one another so that there are never more than two couplers in the same section, with each cable having a length on average equal to that of six concrete sections. The lower slab cables are anchored conventionally into double bosses, thus providing overlapping and total continuity of the prestressing force. These 12 T 15 cables, inside the concrete, are run through metal sheaths and injected with cement grout. In the current part of the deck, because of the type of structure, as explained previously, these first phase cables, although they run continuity in the upper and lower part of the section, throughout the length of the bridge, they are not relieved at the end of pushing. Only the cables reinforcing the prestressing in the first two spans, between C0 and P2, are relaxed at the end of pushing.

The cables of the second family are 10 T 15 S type, class 1860 MPa, placed outside the concrete and arranged inside the central caisson having a polygonal layout. In the current section, this family includes six cables running over the entire length of the bridge, three on either side of the caisson. The cables are anchored into double bosses placed at the middle of the span. Each cable runs through two complete spans plus the two adjacent half-spans to the middle of which they are anchored. Therefore, the length of each cable corresponds to three spans and, at the middle of each span, there is a boss covering one pair of cables. In the two intermediate spans through which they run continuity, these cables are deflected into two deflectors placed approximately at the one-quarter and three-quarter length of the spans. Over the piles, they run over posts forming deflectors. These 19 T 15 cables outside the concrete are run in P.E.H.D. sheaths and injected with cement grout. The P.E.H.D. sheaths pass through the bosses and the intermediate deflectors inside curved metal tubes having a diameter of approximately 180 mm, forming a double lining and ensuring that they are removable. An additional tube is left empty and also arranged in each boss and at each deflector for the incorporation of any additional prestressing (representing 33% of the initial external prestressing).

4.4. The large span over the Marne river

Because of its large span of 93 m, the deck is reinforced in the span over the Marne and, in addition to the current first and second family cables, includes sub-bands of six 27 T 15 S cables having a polygonal layout, off-centered by three metal posts.

These cables are anchored into the caisson at the supports on piles P7 and P8 either side of the Marne span. They are off-centered on the inner side of the deck by three V-shaped posts constituting of metal tubes with the off-centering representing 10.00 m at the central post in the center line of the span, and 6.00 m at the two side posts. For aesthetic and architectural reasons, these six cables are grouped together in one plane in the central part, between the central post and the two sides posts, then fan out between the side posts and the piles.

Similarly to the outer surface prestressing cables, being considered as intermediaries between the outside cables and the guys, the sizing of these sub-band cables allows for a limit of 65% of the guaranteed breakage limit (0.65 $_{\text{foregoing}}$). These 27 T 15 cables are placed in painted metal tubes injected with cement grout. They are easy to access, remove and replace.

4.5. The deck construction method

The deck is constructed by pushing. The deck is prefabricated in successive sections having variable lengths of up to 29 m in a prefabrication area located behind pier C22, to the east of the bridge. After the prefabrication of each section, the deck is pushed over the length corresponding to the prefabricated section.

Because of the specific nature of the transversal section, the deck prefabrication area, with a length of approximately 150 m, includes four separate zones:

- an initial zone at the rear corresponding to the assembly of the metal core panels (adjustment, welding, painting, equipment, testing);
- a second zone corresponding to the casting of the lower slabs with the installation of the stays;
- a third zone corresponding to the casting of the upper slab;
- finally, a fourth zone corresponding to the prestressing of the bridge and the fitting out of the deck.

5. Development of the structure

5.1. Adjustment of lower connection

The initial solution envisaged to connect the plane-tubular web to the higher and lower slabs with the same classical arrangement, i.e. by means of a steel flange and vertical shear connectors.

However, considering the difficulty of a correct concreting of the lower concrete slab under a completely horizontal flange, the contractor imagined a different arrangement for the lower connection.

Lower connection before concreting

In lower area, the tubes and the plane panels of the webs are embedded at a depth of 30 cm in the concrete of the lower slab. The transmission of the slip between steel and concrete is ensured by dowels welded horizontally onto the plane panels and by “dowels effect” of the tubes themselves, enchased in the concrete.

In order to allow a good distribution of the support reactions in the steel webs during launching phases and in service, steel flat bars with a thickness of 40 mm, embedded in the concrete, are welded at the base of steel sheets.

The tubes bring transverse bending rigidity to the web panels and it is then possible to embed the lower slab on them. The resumption of this fixing force is ensured by U-shaped HA32 reinforcement welded along the tubes, which form part of the longitudinal reinforcement of the slab.

A “martyr” steel sheet is placed just above the concrete slab in order to defer the triple point of corrosion at the end of a secondary component by moving it away from the base of the main web.

5.2. Tests on the experimental beam

An full-scale model of the structure was built in order to check on one hand the feasibility of the adopted constructive arrangements and on the other hand to validate the mechanical behaviour of the structure.

An statically determinate beam 4.5 m high, 10.30 m long, weighing 65 tons, resting on simple supports by means ofa steel frames, formed the body of the test model (figure XX). The cross section of the beam consisted of a section of web and parts of the upper and lower slabs.

This test model was monitored with 90 measurement channels connected to various gauges and sensors.

General view of the test model

The principal studied points in tests were:

- distribution of normal stresses in the cross-section under longitudinal forces,
- global displacements of the test model, transverse deplanation of a web panel as well as the ovalization of the tubes,
- distribution of shear stresses in the steel webs
- distribution of the support reactions during launching phases,
- distribution of the normal and shear stresses in the lower connection area.

This model was subjected to various loading cases, representing those which will be applied to the actual structure, made up:

- of a longitudinal prestressing in the slabs (2 12T15 lower tendons and 4 12T15 upper tendons),
- of a maximum SLS support reaction corresponding to launching phases (1200 t) applied under a tube then under a panel with 4 flat jacks.

A very good agreement between the theoretical assumptions of calculation and the actual behaviour of the structure was highlighted with all the tests.

At the end of the tests, the launching support reaction was raised to 2000 t under a panel, i.e. 1.2 times the ULS loads, without any local buckling of the web. Only a local cracking of the slabs, quite normal at this level of load, was noticed.

5.3. Assumptions and calculation models

Various finite-elements models were carried out in order to study the theoretical behavior of the structure. Some modellings included elastoplastic calculations with large displacement formulation in order to evaluate the risks of instability of webs. The results obtained were confirmed by the tests.

These models also help to determine the mechanical characteristics to be introduced into a general calculation model made of 3D beam elements:

- characteristics for forces and stresses calculations,
- shear area of the “equivalent “ composite section, made uniform using equivalence ratios,
- influence of shear lag on stresses calculations, due to the great width of the deck in comparison with spans.

The general model included of course the flexibilities of the supports and the launching longitudinal beams, the erection process, the three-dimensional geometry of tendons and prestressing losses as well as creep and shrinkage of the concrete parts, which made it possible to validate the structure during launching phases and in service.

Actions and combinations of actions were those of Eucocode 1. Stress verifications were carried out in accordance with French codes specifications.

6. The works on site progress

The contract was notified on July 1st, 2001, following a preparation period of six months approximately, and works began in early 2002. Today, deep foundations, the superstructures for the supports, piles and piers are finished.

The prefabrication of the deck should begin in november 2002 and effective pushing into place in december. The normal scheduled cycle is one section per week, with a length included between 25 and 30 m. The construction of the deck is expected to require fourteen months, in may 2004.