THE VIADUCT OVER THE RIVER TARN AT MILLAU

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SUMMARY: The erection of the viaduct over the river Tarn, at Millau in central France, began in October, 2001 and is to be completed in January, 2005. This will be a major step forward in the design of cable-stayed bridges, with a series of six main spans 342 metres long suspended from seven pylons. The road will pass 270 metres above the river, and two of the piers will be about 235 metres tall; with the corresponding pylon 90 metres tall on top, they both will be higher than the Eiffel Tower. Two designs have been developed, one in prestressed concrete and one in steel.

1 THE A75 MOTORWAY

The Millau Viaduct is a key section of the A75 Motorway between Clermont-Ferrand and Béziers, and thus part of a new link between Paris and Spain. Crossing the old mountains of the Massif Central, it will be the highest motorway in France, at the Issartets pass, 1110 metres above sea level.

For the largest part, this motorway has been designed by the technical services of the French Highway Administration, with a special attention for the major bridges. A specific construction bureau has been created in 1989, to pilot the design of these bridges and to control their erection, the Arrondissement Interdépartemental des Ouvrages d’Art de l’Autoroute A75 (AIOA-A75), directed by Georges Gillet (figure 1).

Figure 1 : The A75 Motorway and its major bridges
The SETRA – the design office of the Highway Administration in France – has been in charge of the design of some of the major bridges, but also had a major influence on the design of the other ones through its participation to all project teams as consultant and supervisor. Being head of the large bridge division in the former period, we have developed or inspired the conceptual design of all these bridges, including the last one as private consultant:

- the Viaduct over the river Truyère at Garabit;
- the Piou and Rioulong viaducts;
- the La Planchette Viaduct, near the village of Chirac;
- the bridge over the river Lot at La Mothe;
- the Antrenas tubular arch;
- the Truc de la Fare overpass, a prestressed concrete slab suspended from below by cables;
- and the viaduct at Verrières.

In the same time a great care was given to the integration of the motorway in the landscape, specially under the influence of Marc Marcese and Bernard Lassus. Not forgetting two major tunnels at Monjézieux and Le Pas de l’Escalette.

2 THE MILLAU PROJECT

2.1. But the greatest challenge for the completion of the A75 motorway was to cross the wide and deep Tarn valley in the Millau area.

The first road alignments were proposed in 1987 by the CETE Méditérannée. One was passing East of Millau, with two major suspension bridges from plateau to plateau to cross the Tarn and Dourbie valleys, but with no possible link with the city of Millau; it was immediately abandoned for this reason. Another was passing at the limit of the city, deep in the Tarn valley, to climb the Plateau du Larzac to the South in the same area where the existing road, RN 9, passes; some were in favour of this alignment which was supposed at low cost, but with long and stiff slopes it was a very serious handicap for the heavy traffic. The last one crossed the river Tarn West of Millau, with a classical cable-stayed bridge, and climbed the Plateau du Larzac taking advantage from an existing depression, the Cirque d’Issis; but this depression had been produced by the collapse of the hard limestone layers, undermined by the underground water running from the plateau, and the road would have had be installed on some unstable layers of soft clay. This alignment was really impossible.

2.2. As the simple acceptable alignment was along the existing RN 9, and was opposed in the same time by the local authorities who refused having the motorway almost in the city, and by most engineers due to its poor characteristics, a new alignment was proposed, far to the West, turning around the most abrupt relief of the Larzac Plateau. But immediately new problems arose: the journey was increased by about five kilometres, some geotechnical difficulties could not be avoided, and the inhabitants of the concerned villages opposed.

2.3. As the situation appeared desperate, we have been asked to check – together with Georges Gillet, Emmanuel Bouchon and Philippe Gaudemer – if we were sure that no alignment was possible just West of Millau. From the Larzac Plateau we could imagine one in May, 1989. Descending from the North and the Causse Rouge along an adjacent thalweg, the alignment crossed the river Tarn with a classical cable-stayed bridge, and reached an intermediate plateau on the left bank, the Plateau de France where an interchange could be settled to join local roads. From there a curved viaduct – made of two independent structures – rised to reach the higher part of the cliff dominating the valley to the West, the Caussonus, to penetrate into a layer of hard limestone with a
tunnel made of two parallel tubes (figures 2 and 3).

The alignment has been improved with two experts, Marc Panet and Marcel Rat, a geotechnician.
and a geologist, and later developed by the CETE Méditerrannée.

2.4. But, as soon a good alignment could have been selected, we realized that the simplest solution consisted in directly passing from North to South over the valley with a high viaduct, from the Causse Rouge to the North to the Plateau du Larzac to the South (figure 4).

The “logical” solution was a long suspension or cable-stayed bridge, with a span of about 800 metres to cross the deeper part of the Tarn valley and the river, the southern pylon being located on the Plateau de France on the left bank (figure 5). But in our opinion high pylons would have been intrusive in the site, and we could not suggest a solution of this type.

We considered much more adapted to the site a bridge with repetitive spans, with no emphasis on the crossing of the river, because due to the numerous meanders of the river Tarn the deeper part of the valley can be seen from almost nowhere ; from almost any point in the area the valley can be seen only at the Plateau de France level and above, and the bridge design has to be adapted to this impression (figure 6). But of course it has to have very long spans due to the depth of the valley. This is why we imagined a viaduct with several cable-stayed spans, from four main spans about 450 metres long to seven main spans about 300 metres long. With Emmanuel Bouchon we selected the last option, with eight pylons and seven main cable-stayed spans 290 metres long or six main cable-stayed spans 320 metres long (figure 7) for two reasons :

Figure 6 : The final project seen from the Millau old city tower

Figure 7 : Two preliminary options with six or seven main spans (July, 1990)
- a span of 300 metres allows for crossing the deeper part of the Tarn valley, on condition to accept two piers about 240 metres tall. With longer spans, a pier would be located in the abrupt slope dominating the left bank of the river where it appears difficult to erect one.
- Spans 300 metres long are more adapted than longer ones above the Plateau de France where piers are “only” 100 to 150 metres tall.

2.5. This conceptual design was developed in 1989 and 1990. Unfortunately, to show the size of the structure we had the idea to place on the same drawing and at the same scale an image of the Eiffel Tower and of the Garabit Viaduct, the famous constructions by Gustave Eiffel (figure 8). The impact has been enormous, everybody having some responsibility connected to the project, plus hundreds of architects, engineers and journalists suddenly aiming at having some influence on the design.

Figure 8 : The controversial drawing with the Eiffel Tower (July, 1990)

3 THE DEVELOPMENT OF THE PROJECT

3.1. As for any other large bridge, the Millau viaduct project had to follow a rather classical process. In a first step it has been necessary to select one of the two road alignments, the low one with the classical cable-stayed bridge over the river Tarn, the curved viaducts and the tunnels, or the high bridge proposed with multiple cable-stayed spans as a possible solution. Some drawings were made with the participation of the architect Berdj Mikaelian; only one of the two parallel curved viaducts was shown, though the existence of the two tunnels at the South end absolutely required two (figures 9 and 10).

Figure 9 : Perspective view of the viaduct over the Plateau de France, only one viaduct for the “low option” (Berdj Mikaelian, 1991)  
Figure 10 : Perspective view of the cable-stayed option over the plateau de France (Berdj Mikaelian, 1991)
The low option had evident drawbacks: a route longer by more than one kilometre, needed to go down in the valley and up again, from one plateau to the other, with slopes limited at 4%; a descend from South to North, out of the tunnel, at 4% with a curvature radius of 900 metres; as in addition this side is to the North, it might make the road very dangerous with ice in Winter; and finally a very sharp curve for the traffic from the South to the local areas on the left bank of the River Tarn, at the entrance of the interchange on the Plateau de France. Even more, with the longer alignment, the cable-stayed bridge, the curved viaducts and the tunnels, cost analyses made in 1990 by Soprese and Philippe Drisin could show that the lower route was more expensive than the direct one from plateau to plateau.

For all these reasons the direct alignment was preferred and officially adopted by the Highway Director on October 29, 1991. When he discovered the project, as a member of an international panel of experts in charge of the project evaluation, Jorg Schlaich immediately questioned the selected alignment; but after a visit of the site he totally supported the decision.

3.2. According to the rules for large projects, the next step was the definition of the conceptual design. The SETRA had to compare different possible solutions to propose the best one; but in this special case the preliminary analysis was made into two successive steps.

The first one, completed in July, 1992, consisted in a review of five families of solutions (eight when separating steel from concrete):

- prestressed concrete box-girders of constant depth built by the cantilever method, with equal spans 120-140 or 170 metres long;
- steel box-girders of constant depth incrementally launched, either with a concrete top slab (for rather small spans) or with an orthotropic deck, with equal spans 120-140-170 or 200 metres long;
- prestressed concrete box-girders of variable depth built by the cantilever method with equal spans 170-200 or 240 metres long;
- steel orthotropic box-girders of variable depth with equal spans 200 or 240 metres long;
- box-girder bridges with a main span of variable depth over the river Tarn and the deeper part of the valley, and with other spans of constant depth; the spans were respectively 240 and 140, or 280 and 160 metres long: the last solution of the type being with three spans of variable depth, 250 metres long, and with access spans 160 metres long; either in prestressed concrete, built by the cantilever method,
- or in steel, with an orthotropic structure. Then the access spans of constant depth were incrementally launched;
- a “classical” cable-stayed bridge over the river Tarn and the deeper part of the valley, with a span 400 or 450 metres long and with access spans 170 metres long; the structure being an orthotropic box-girder could have been incrementally launched from both sides, except for a very small part of the main span if 450 metres long;
- and finally the prestressed concrete solution with multiple cable-stayed spans, six main spans 320 metres long suspended from seven pylons with two intermediate piers in each side span.

3.3. From this review seven solutions were selected for a more detailed preliminary design, and developed with again the participation of Berdj Mikaelian. But one of the conditions given by the authorities was to limit the analysis to the technical aspects of the project, to prevent premature decisions on the architectural evolution of the design (figure 11).

- A classical orthotropic box-girder of constant depth with equal spans 200 metres long, incrementally launched.
- A classical box-girder bridge of variable depth in prestressed concrete, built by the cantilever method, with equal spans 240 metres long.
- A similar solution with three spans of variable depth 250 metres long and with access spans of constant depth 160 metres long.
A third solution of this type, with only one main span of variable depth 280 metres long and access spans of constant depth 160 metres long.

- The alternative solution with an orthotropic box-girder, with the same main span of variable depth over the river Tarn, 280 metres long, and with access spans 160 metres long incrementally launched.

- Another steel orthotropic solution, with a main cable-stayed span 400 metres long over the river Tarn, side spans 185 metres long and access spans 170 metres long. All the steel structure was launched from both sides to be closed at mid-span over the river.

- And still our preferred solution in prestressed concrete with six main cable-stayed spans 320 metres long and seven pylons (figure 12).

4 THE CONCEPTUAL DESIGN OF THE CABLE-STAYED SOLUTION WITH MULTIPLE SPANS

4.1. Since such a solution rose many new questions, we had to devote our greatest efforts with Emmanuel Bouchon, Daniel Lecointre and Christophe Outteryck for the development of the cable-stayed solution with multiple spans. A bridge with multiple cable-stayed spans rises two major problems the solutions to which are almost antagonist.

- When one span is loaded by the traffic, tension increases in its cable-stays, and the adjacent
pylons deflect towards the span. As there is no back-stay in the adjacent spans, the deflection of these pylons lifts the cantilevers (and spans) adjacent to the loaded bay. As spans can be loaded one after the other, each span alternatively receives bending moments upwards and downwards; thus stress variations can be very high in the deck (figure 13).
To reduce traffic induced deflections, upwards and downwards, different solutions can be proposed. For small and medium spans, it is possible to limit deflections by designing a rather rigid deck. But for longer spans, as in the Millau viaduct, it is necessary to design rather rigid pylons and to take advantage of the rigidity of the piers below the deck.

- This is why the most efficient solution consists in designing continuous towers, with the pylon in the continuity of the pier below. The simplest case is for bridges with a lateral suspension, with one tower leg on each side of the deck which can pass through the pylon.

- But with very high piers as in the Millau viaduct, we considered extremely inelegant to have framed pylons and lateral suspension; the Mezcal bridge, in Mexico, clearly shows that proportions and shapes are far from the structural elegance we aim at (figure 14). We considered necessary to have axial pylons and suspension. In this situation, to produce the desired participation of piers to the global rigidity, it is necessary to have rigid connections between piers, deck and pylons, or any other solution which allows for a transfer of bending moments to piers.

Figure 14: The Mezcala bridge, Mexico, with lateral suspension and pylons (photo Freyssinet)

- But a rigid connection between piers and deck prevents the development of length variations in the deck due to temperature variations and to concrete creep and shrinkage in prestressed concrete structures, not forgetting shortening effects produced by prestressing forces.

4.2. A logical solution consisted in having a rather rigid deck – a box-girder about 5.00 metres deep – resting on a series of rigid piers below the pylons through two lines of pot-bearings; fixed bearings on the four central piers, and sliding bearings on the extreme piers, one to the North and two to the South side.

But with the very high loads due to the bridge and pylons weight, friction forces on the sliding bearings would have produced very important bending moments in tall piers. In addition the longitudinal displacements due to temperature variations, as well as concrete creep and shrinkage, could reach 50 to 60 centimetres, off-centering loads and needing very specific provisions. Finally, we considered difficult to control the movements of the sliding bearings due to thermal effects, since they are non-linear and non-elastic, and we were anxious of their importance.

For all these reasons we have eliminated this solution.
4.3. We decided to rigidly connect the piers to the deck, and considered the possibility of designing rigid piers on condition to have an expansion joint at mid-span in the fourth main span from the North.

But a classical expansion joint would have increased the bridge flexibility, a situation which could not be accepted for such a type of structure. To transfer bending moments through the joint, we designed a “drawer-beam” to be installed inside the box-girder, with two lines of bearings on each side of the joint, up and down, to transfer bending moments in both directions (figure 15).

![Figure 15: Principle for a “drawer beam” transferring bending moments through an expansion joint at mid-span](image)

But it appeared very delicate to locate a rigid drawer-beam in a more or less stream-lined box-girder, and finally René Walther – another of the experts of the international panel created to evaluate the project – strongly recommended to eliminate any intermediate joint and so we did.

4.4. Finally, we decided to divide the extreme piers – still one to the North and two to the South – into two twin shafts to produce in the same time a high flexural rigidity and a great flexibility as regards longitudinal deformations in the deck. Emmanuel Bouchon increased this longitudinal flexibility by installing one line of fixed bearings on top of each of the two shafts of these piers.

Technically, all problems were conveniently solved.

4.5. The analysis was completed with an evaluation of wind forces.

Practically, due to the site configuration the bridge is located 150 metres above the plateau, the deeper part of the valley having almost no influence as regards wind effects due to the numerous meanders of the river Tarn. Nevertheless, this leads to very high winds.

Before having very good data we could evaluate wind forces and from them the dimensions of the pier cross-sections.

With a classical box-girder bridge made of a series of equal spans 240 metres long, for example, a parabolic variation of the cross-section from the pier head is not convenient: in the upper part the dimensions increase too slowly and the cross-sections cannot resist wind forces; on the other hand a linear variation of dimensions appears heavy and inelegant; we had to adopt an intermediate solution, with a straighter parabolic shape.

Fortunately, one of the advantages of the cable-stayed solution is the lower structural depth of the deck, and its better shape aerodynamically. With the corresponding reduction of wind forces, the cross-section can vary parabolically from the pier head, from approximately 10 x 9 metres to 24 x 14 metres at the basis of the two taller piers.

5 THE PROJECT DEVELOPMENT

5.1. When the Millau project was initiated, in the late eighties, it was anticipated that the design
would be developed as for the Normandie Bridge within a design team led by the SETRA and made of several design offices selected for their qualification.

And as for the Normandie Bridge it was decided to constitute an international panel of experts for the project evaluation.

5.2. This panel of experts has been settled in 1993 and later met at each major step of the project development. Chaired by Jean-François Coste, it comprises several structural engineers (René Walther, Roger Lacroix, Jean-Claude Foucriat with also Jean Pera and Jorg Schlaich at the initial steps), a wind expert (Alan Davenport), geotechnicians (François Baguelin and Jean-François Corte) as well as architects, landscape architects and specialists of bridge aesthetics (David Billington and Bernard Lassus).

5.3. In the same time the new Highway Director, who was not convinced by the orientations proposed by the SETRA, decided to organize some competition to develop other concepts than those already suggested.

Eight design offices (Jean Muller International, Setec, Ove Arrup, Secoa, Ingerop, Sogelerg with Serf and Structures, Europe Etudes Gecti, Sofresid) and seven architects (Sir Norman Foster, Alain Spielmann, Jean Berlottier, Francis Soler, Denis Sloane, Jacques Hondelatte, Philippe Fraleu) were separately consulted.

They were asked to give their opinion on the SETRA designs, to propose improvements and amendments – as well as architectural treatments for the architects –, and to suggest new ideas.

This consultation took place between November, 1993 and February, 1994. Of course, we cannot describe the different proposals which remain the property of their authors and the French Administration, but we can say that rather few structural ideas emerged.

- A design office and an architect proposed an arch bridge above the deeper part of the Tarn valley, a solution we had eliminated from our analysis due to the very large arch span, and because it did not correspond to our analysis of the site as explained above.

- Another design office proposed to replace the solution with a unique cable-stayed span over the river Tarn with a span suspended from below by cables (sub-bended) ; this appeared a rather logical solution, perfectly adapted to a steel structure launched from both ends and closed in the long span across the river, which can be sub-bended after closing.

- An architect proposed a solution with a series of long spans – 320 metres long –, all sub-bended.

- And a design office proposed a very long cable-stayed span (about 900 metres), a solution already contemplated but eliminated due to the pylon size.

5.4. Some experts of the panel suggested the organization of a design competition, in the same time as some opinions were given. But due to the number of the members and to their different goals and origin, it has not been possible to give a clear orientation to the project.

In this period Georges Gillet collected basic data. The most important ones concerned wind conditions and costs.

A pylon, 40 metres high, was installed by the CSTB on the Plateau de France to record wind data. The three components of the wind instantaneous velocity were recorded at different levels to build a wind model and to have a correlation with the closest meteorological station, at Millau Soulôbres. In addition a Sodar was installed in the deeper part of the valley, on the left bank of the river Tarn, to get more information about the distribution of wind velocity and turbulence in the site.

And finally, the CSTB made a wind tunnel model of the site to evaluate the average angle of attack of the different winds, the stronger ones coming from West and from South-East.

As regards costs, a second analysis was made by Soprese and Philippe Drisin for a better
evaluation of the solution with multiple cable-stayed spans, which was still developed by the SETRA. From the reactions of the architects who took interest in this solution in their proposals, we considered an improvement to eliminate intermediate supports in the side spans. Daniel Lecointre and Christophe Outteryck controlled that the second intermediate pier – closer to the first pylon – could be easily eliminated; since the main piers have a high rigidity to balance live loads in the typical spans, they also can balance them in side spans. Eliminating the second intermediate pier was more critical, but it appeared possible with the final span distribution (figure 16).

Figure 16 : Elimination of intermediate supports in side-spans (SETRA, 1994)

5.5. Meanwhile, in 1994-1995 the project became a public affair. Though almost all local authorities supported the project and road alignment, some opposition came from ecologists in the area, more or less supported by national media. And it appeared very clear that a design developed by the French Administration would receive strong criticism, whatever it would be.

Engineers were accused of building ugly concrete structures – a situation very hard to accept for us just after having erected the Normandie Bridge – and the Highway Director, still very far from being convinced by the design with multiple cable-stayed spans which was our recommendation, decided to develop five parallel designs.

6 THE FIVE PROJECTS IN COMPETITION

6.1. The idea was not a design competition between five teams, but the development of five selected projects to completely explore the possibilities and select the best one.

The projects were as follows:
- a viaduct, in steel or concrete with multiple cable-stayed spans;
- a viaduct with continuous spans of variable depth in concrete or composite;
- a steel viaduct with multiple sub-bended spans, or with a unique sub-bended span over the River Tarn;
a concrete bridge with an arch having an opening of about 600 metres above the River Tarn;
and a steel viaduct with continuous spans of constant depth, with possibly a specific structure
over the River Tarn.

The different teams were built from the design offices and architects already consulted in 1993
who made attractive proposals, the project they had to develop being selected according to the
solutions they proposed.

Though this was not a real design competition, it was decided that the solution would be selected
by a Jury constituted for this purpose, made of twenty members: some local politicians, some
architects, some structural engineers and some directors of the qualified administrations.

6.2. In such a situation the SETRA could not be anymore responsible for the design, which logically
was to be given to the team developing the selected project. Being deeply interested in this major
construction to which we already had devoted much time, we decided to leave the SETRA in order
to take part in the team in charge of the solution with multiple cable-stayed spans, which was by far
the most adapted to the site in our opinion.

6.3. The different teams worked from November, 1995 to April, 1996. But we could not work the
whole time in the team we joined, the authorities considering that our previous participation in the
project when at the SETRA was an advantage for our team, and we had to withdraw.

7 THE 1996 PROJECT

7.1. The team in charge of the solution with multiple cable-stayed spans was made of three design
offices – Sogelerg, the pilot, Europe Etudes Gecti and Serf – and the architect Sir Norman Foster.
Some basic options were selected from the beginning, such as:
- eliminating all intermediate supports in side spans, as suggested by the architects in 1993, in
  order to limit the supports to the main ones for a very clear concept. This finally led to rather long
  side-spans (204 metres for typical spans 342 metres long), but reducing them was automatically
  reducing the height of the end piers and decreasing their flexibility for longitudinal movements.
- Adopting a curved alignment for the bridge, following a recommendation by Roger Lacroix
  and Bernard Lassus, to give to the users passing on the bridge a more attractive view on the
  structure. Though our initial opinion was to design a very straight line, to evidence more clearly the
  passage of the motorway above the valley, a curved alignment appeared more sensible.

7.2. The shapes have been selected in a series of discussions with Sir Norman Foster in his office.
We have explained the two main problems, illustrated by drawings:
- the first one was to evidence the necessary distribution of rigidity between deck and pylons. A
  very rigid deck with a rather slender pylon above as in the design previously developed by the
  SETRA; or a more slender deck with a rather rigid pylon; or a very rigid pylon – either made of
  two columns connected by the anchorage box or any other structural element, or having the shape
  of an inverted V longitudinally, evidently more elegant – which can suspend a flexible deck
  (figure 17).
- The second one to evidence the necessary flexibility of the end piers as regards horizontal
  forces. With the corresponding options: a large difference in shape between the central and very
tall piers, and the other piers; or a unique shape of piers, with twin flexible shafts in the higher part
and a large box-girder below to resist wind forces and second order effects (figure 18).
In the perfect line of his 1993 drawings, Sir Norman Foster selected the options we also
preferred, leading to the lightest, clearest and simplest concept: inverted V pylons, and piers made
of a wide box-girder in the lower part, dividing into two flexible shafts above. Allowing for a
relatively slender box-girder deck, more streamlined than in the initial SETRA design.

The detailed shapes were developed by Tim Quick, in close cooperation with the other engineers, Bernard Gausset, Claude Servant, Jean Louis Michotey and their teams (figure 19).

7.3. The concrete option was designed from these ideas and the initial SETRA project, with no major drawback. The erection by the cantilever method on mobile carriages is not extremely simple, since it is necessary to lift concrete and the reinforcement from the bottom of the piers, and to transport them later along the cantilevers, but there is no strong obstacle except for wind effects during the cantilever erection.

The situation appeared very different for the steel option. It is not possible to lift from the deck the successive segments, since there is not an access everywhere on the ground. This is why we proposed launching the steel structure from both ends, with a temporary support in the middle of each span, except the one over the river Tarn.

But the evaluation of the time necessary for construction has shown that it is reasonably impossible to design a composite deck and concrete pylons: after the installation of the steel structure, a long time would be necessary to erect concrete pylons, and the concrete top slab could be concreted only later, after the installation of cable-stays.

This is why we decided for an orthotropic box-girder for the deck, and for steel pylons which
could be launched in the same time as the deck. We must confess that we had not checked, at the time, if the presence of the pylons, increasing wind forces, could be a problem.

7.4. The Jury met on July 8 and 9, 1996, and selected this project, preferred to the other four. The official decision was taken by the Minister on July 15, 1996.

8 THE FINAL 1998 PROJECT

8.1. After the finalization of the contract, the project was developed by the same team which we could join again. Initially to be established between July and December, 1997, it only ended in September, 1998 due to aerodynamic problems.

8.2. A certain number of comments were made by the authorities on the 1996 project, though selected, and many amendments or improvements were requested.

For example, the road alignment was slightly altered to avoid a small but deep thalweg on the left bank of the river Tarn, in the stiff slopes of the Plateau de France. The curvature radius was decreased from 30 000 to 20 000 metres.

On this alignment the spans remained 204 - 6 x 342 and 204 metres. Considering the rather long side spans and the corresponding problems, we were prepared to amend the span distribution to something like 193 - 6 x 346 and 193 metres, but Georges Gillet had just completed all soil tests at the pier locations and it was decided to maintain the spans as previously proposed.

The abutments were designed with the architect; these concrete structures are made of a central and rather narrow rectangular block, with an overhanging element on each side to extend the shapes of the bridge deck. The front wall is inclined towards the valley to give the most dynamic impression.

8.3. But the greatest efforts were made to improve the shapes of the piers and to link them to those of the deck.

From the curved – and rather weak – shapes of the 1996 project, the architect developed an improved design with a triangular scheme; after some discussions, it was decided to give to the deck also a triangular shape for homogeneity, and the pylons received an adapted profile to respond to the rest of the structure.

8.4. As this new shape for the pylon was slightly less favourable, but also considering the bridge curvature and the importance of wind forces, its width (the dimension transversally to the bridge) finally had to be increased from 3.00 to 3.50 metres.

8.5. But the main problem came with the results of the wind tunnel tests performed by the CSTB. It appeared that a triangular shape for the deck is highly sensible to the profile rugosity; a very smooth surface generates vortices at the lower angle which increase the drag coefficient; the variation of the lift coefficient as a function of the angle of attack also becomes far from linear.

These results raised many discussions as well inside the design team as within the French Administration.

Some considered that scale effects created the problem in the wind tunnel, which might disappear in the site with the wind turbulence; but we considered dangerous, and against engineering logics and ethics, to maintain a solution with potential problems.

This position, strongly supported by Sir Norman Foster who stated that architectural elegance could not be achieved against the need of an efficient structural behaviour, was followed by the design team and the French Administration, mainly due to Claude Bois who insisted for the
development of a safe project.

The design was then redeveloped, with again a trapezoidal shape for the deck (the bottom flange being narrower than in the 1996 project, to be closer to the triangular shape and aerodynamically more streamlined), and the architect created a new section for the piers in perfect coherence with the deck.

The final wind tunnel tests confirmed that the new shapes are well streamlined, and not sensible to the profile rugosity (figures 20 and 21).

Figure 20 : Compared shapes of the 1996, 1997 and final projects (concrete option)

Figure 21 : Aerodynamic coefficients of the 1997 and final projects (smooth and turbulent flows)

It is to be mentioned that Georges Gillet commissioned two numerical analyses of the profiles, one by ONERA and the other by EDF, which gave interesting results but could not be conclusive. This new numerical approach – which improves very quickly – cannot replace classical wind tunnel
tests but can be used to compare different profiles, or evaluate scale effects or the influence of test conditions.

It is finally worth being mentioned that due to the very large flexibility with regard to longitudinal forces of the higher part of the piers, divided into twin shafts, turbulent winds generate rather important longitudinal movements of the deck and important bending forces in the upper part of the twin shafts which are rigidly connected to the deck in the concrete option (except for the two end piers as already shown). Emmanuel Bouchon, who evidenced the problem when checking the project, suggested the installation of hydraulic dampers at the abutments, a solution which was adopted and improved by adding springs to dampers.

8.6. From this point the design of the prestressed concrete solution was smoothly developed (figure 22) with no other problem than the stability of the cantilevers during erection: due to the wind intensity at the deck level, and the large flexibility of the structure in the construction situations, it appeared necessary to install three series of cables to control the four main modes excited by the wind turbulence: torsion of the pier, longitudinal and horizontal displacement produced by the flexibility of the twin shafts in the upper part of the pier, transverse bending of the pier, and finally vertical oscillations of the deck.

Figure 22 : The final Millau project (concrete option, 1998)
8.7. As a transition to the steel alternative, the pylons have a composite design directly inspired from the Normandie Bridge: the cable-stays are anchored in an axial anchorage box, in steel, divided into a series of elements to allow for their installation. This anchorage box is of course of very large dimensions due to the pylon shape, an inverted V longitudinally as already shown.

8.8. Our steel solution proposed in 1996 received strong criticism from the steel producers and contractors who considered that the temporary piers – necessary for launching the deck – were extremely costly and a handicap in the competition with concrete. They recommended to amend the solution, with another construction technique.

But a classical construction by the cantilever method was only easy for the cantilevers supported by the first two piers on the Plateau de France (P4 and P5): it is almost impossible to rise from the ground a steel segment from the cantilevers on several piers (P3 – P6 and P7) due to the site configuration. This is why we developed a progressive cantilever construction technique, from both ends, with segments 16 metres long, using temporary cable-stays when passing a mid-span section. Only the cantilevers above the fourth pier (P4) would have been erected by the classical cantilever method.

With this solution it was possible to have pylons in concrete, erected after the installation by almost classical techniques of a first steel segment upon the pier.

8.9. The analyses developed by SERF have shown that we could not have a rigid connection between the piers and the deck: as the steel deck is much more flexible than in the concrete alternative, a greater part of bending moments produced by traffic loads passes to the piers; and as the pier twin shafts are extremely slender, they cannot resist these bending moments generated by traffic loads.

This is why we have one line of fixed bearings on top of each of the two shafts of all piers in the steel solution, when we have such bearings only on the extreme piers (P1 and P7) in the concrete solution to adapt to length variations as shown before.

The deck has to be tied down to those piers by vertical prestressing tendons, to resist uplift action of wind effects in ultimate conditions (figure 23).

8.10. But the main problems came with the analysis of construction situations.

Some had been clearly foreseen:

- the steel segments have to be moved on one side of the deck – the inner side –, to avoid the axial pylons and cable-stays. This condition limits their length to 16 metres as already said, being clear that they will partly pass over the void.

- A special derrick, anchored to the deck to limit its weight, has to be installed at the cantilever end, to take the new segment, to turn it in order to place it above its final position, and finally to descend it to be attached to the cantilever end. After welding the joint and installing the corresponding cable-stay, the derrick has to be moved on the newly installed segment to prepare a new operation.

- The temporary cable-stays which suspend the part of the cantilever beyond mid-span have to be anchored in the higher part of the pylon, which is rather narrow, to specific elements cut after completion of the following span, when these temporary cables can be removed.

- To avoid disturbing the balance of weight in the structure, the temporary backstays which equilibrate the temporary cable-stays in the long cantilever are anchored in the deck at the previous pylon level, on the outer side due to the curvature of the bridge alignment.
But two major problems had been underestimated.
- The curvature of the bridge alignment is not a serious handicap in the completed bridge, with a span of 342 metres; but this is a very serious question in a cantilever of about 330 metres. It appeared necessary to outcenter the temporary cable-stays beyond mid-span in order to limit torsional forces in the deck and transverse bending in the pylon.
- And wind effects are very important on such a long cantilever, calling for stabilization cables anchored in the ground from the front part of the cantilever (figure 24).
8.11. This is why we were very far from being convinced, after having completed the project, that the steel solution could be competitive.

But the French steel industry took a major interest in the Millau project, and decided to develop another construction technique in order to prepare the competition which was to take place in the last months of 2000. A contract was given to Greisch, and during a conference in April, 2000 in Millau, the steel industry proposed a solution consisting in launching an orthotropic box-girder from both sides with the help of temporary supports, one in each span except the deepest one (between P2 and P3) where the closure is to take place. The composite option was eliminated to shorten the construction time, and pylons are in steel for the same reason.

In fact the steel industry re-invented the 1996 steel project, which we had developed and which had been criticized at the time.

9 THE CONCESSION

Finally the French Government decided to build the bridge within a concession, the construction cost being paid by tolls.

This changed very much the initial conditions, with very important results:
- the first one being that the design team could not be involved in the competition between the different candidates to the concession.
- As the Government decided to maintain the project as it had been developed, since it had been declared of public interest after a public inquiry and approved by the appropriate authorities, it has been rather difficult to build specifications clarifying the concessionaire responsibility. The decision was to consider mandatory the shapes, and leave all responsibilities to the concessionaire for the development of the technical aspects of the design: dimensions, construction techniques etc…

The candidates received the final documents in June, 2000 and submitted their bids on November 21, 2000.

On February 26, 2001, the Eiffage Group has been declared potential winner of the competition and on October 10 has been officially declared concessionaire of the Millau viaduct under the name of Compagnie Eiffage du Viaduc de Millau.

10 CONSTRUCTION

10.1. The Eiffage Group made a proposal for each of the two options, steel and prestressed concrete. For the prestressed concrete option, Eiffage Construction developed a solution with heavy precast segments, about than 200 metric tons in weight. But the group, including a steel contractor – Eiffel Construction Métallique – could prepare a very efficient steel option (figure 25).

10.2. As in the 1996 project and for the solution developed by the French steel industry in 1999-2000, the steel orthotropic box-girder is launched from both ends with the help of temporary supports. As a direct result the pylons have been redesigned in steel, exactly as in the 1996 project and as recommended by the steel industry and for the same reasons, to shorten construction time (figure 26). But in the Eiffage final project only the front pylon is launched with the deck, and it is shortened, limited to the lower part in which cable-stays are anchored to reduce transverse wind effects.

The main improvements in the project come from erection techniques.
10.3. The temporary piers, one in each span except the one above the river Tarn itself, have the shape of a tubular truss, assembled element after element from bolted bars. When a new element is assembled, at the bottom of the pier, the whole pier is lifted and a new element is assembled at the bottom (figure 27).

The head of each temporary pier is equipped to receive the launching equipment.
10.4. Due to the importance of the pier height, it was impossible to use classical launching techniques. Marc Buonomo – taking some inspiration from the launching system used for the erection of the access spans of the Normandie Bridge – developed with Enerpac a specific solution: the bridge is pushed forward from each support, pier or temporary support, with four launching machines commanded by a central computer, with a series of sensors to control the relative displacements. If all launching machines work in the same time, as they have to do, and progress at the same controlled pace, launching forces are purely internal on each support with no bending force in the piers.

The first launching operations, on the South bank evidenced the system efficiency.

10.5. Except on the temporary piers of the side-spans which are only equipped with two launching machines, each pier or temporary pier receives two lines of two launching machines, at a distance of about 20 metres.

The shape of the temporary pier heads has been adapted to this situation, but it has been extremely difficult to install a temporary frame on the final concrete piers to support the two lines of launching machines on the outside, and to transfer to concrete the very important construction loads (figure 28).

10.6. The closure between the two cantilevers will take place in Spring or Summer, 2004.

The two front pylons (one coming from each side) will be completed by a top element installed with a crane, and the last cable-stays installed and tensioned.

Each of the other pylons will be completely fabricated, transported on the bridge with crawlers and lifted with the help of an adapted tower. Then the cable-stays will be installed and tensioned by Freyssinet.
10.7. Even if the structure is mainly made of steel, the construction of piers cannot be underestimated: the taller one (P2) will be 242 metres high; it will be the tallest pier in the world by far.

After some debate, the higher part of the piers has been vertically prestressed, to resist to higher wind forces for the central ones, and to limit tensile stresses and cracks in the end-piers which are more sensible to temperature effects.

The concrete strength has been easily above the specified 60 MPa.

Under the direction of Jean-Pierre Martin construction progresses very efficiently and the last pier will be completed in October, 2003.

10.8. The execution design for the steel parts of the bridge is developed by the Bureau Greisch, which is also in charge of the global computations. The execution design of the piers and abutments is developed by EEG Simecsol, SERF, Sogelerg and Eiffage TP.

The control of both design and construction has been given to SETEC and the French Railways (SNCF) under the supervision of the Compagnie Eiffage du Viaduc de Millau, of which we are consultant.

11 CONCLUSION

The Millau viaduct is with the Rion-Antirion bridge, in Greece, the first example of a new type of bridges, cable-stayed bridges with multiple spans; a new type of bridges extremely well adapted to wide crossings with a series of long spans, to cross wide rivers or sea channels.

Many different solutions will be developed in the next few years, on occasion of new projects, and there is no doubt that those two pioneer constructions will inspire them.

But the Millau viaduct – as all large projects – also has a history which is as important as its technical aspects, at least to understand how projects can emerge and develop. And finally, the viaduct will be an extremely elegant structure spanning lightly above the deep valley.