The design of the Millau Viaduct

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Summary

The Millau Viaduct is a structure costing 320 million euros, financed and constructed by the EIFFAGE group under concession from the French government. The Compagnie Eiffage du viaduc de Millau, a subsidiary of EIFFAGE, is owner of the structure for 75 years. The viaduct, 343 m high to the top of the pylons, is the last link in the A75 Clermont Ferrand-Béziers motorway. The search for an aesthetically pleasing structure led to the choice of a multi cable-stayed viaduct with slender piers and a very light deck, touching the valley at only seven points. The precision required for each technical phase demands multiple checks, notably by GPS. A toll barrier, whose canopy will be built using CERACEM (BFUP), will be constructed approximately 6 km north of the viaduct at Saint Germain.

Keywords: construction; launching; prestressing; cable stay; pylon; orthotropic deck; bearing; prefabrication; temporary support.

1. Introduction

The Millau viaduct, the biggest civil engineering structure on the A75 motorway, carries the latter over the Tarn valley between the Causse Rouge to the north and the Causse of the Larzac to the south, 5 km west of the town of Millau.

Photo 1: General view of the viaduct at the beginning of February after launches L8S and L4N

The concession for the financing, design, construction, operation and maintenance of the viaduct has been made by the French government to the Compagnie Eiffage du Viaduc de Millau (CEVM) by virtue of a decree published in the Official Journal of 10 October 2001. The concession is for 75 years. However, the concession contract stipulates a "useful project life" for the viaduct of 120 years.

The table in figure 1 provides an overview of the general project organisation put in place by EIFFAGE.

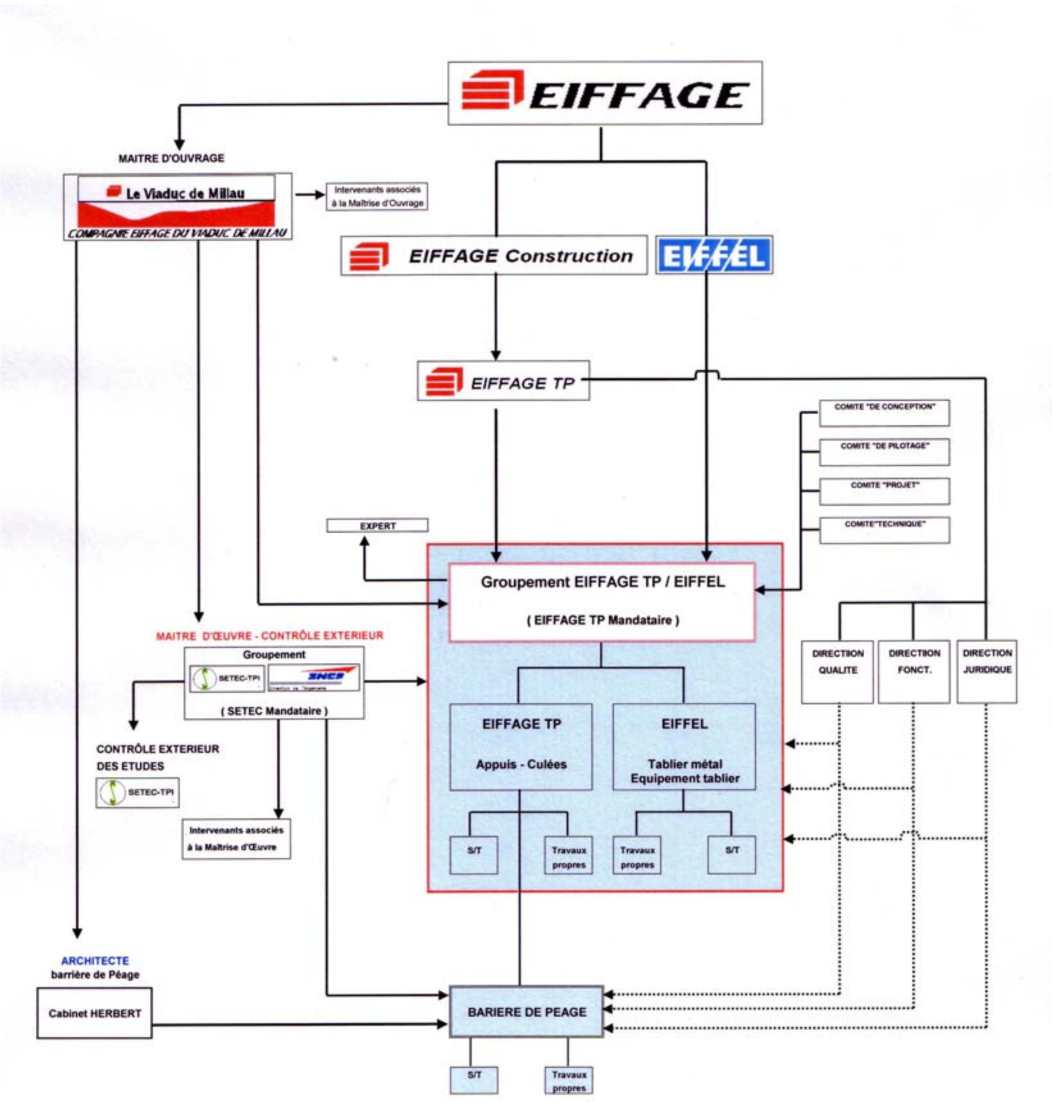


Figure 1: General organisation chart of EIFFAGE

2. The main aspects of the design

2.1. Requirements of the contract specifications

The contract specifications imposed the following prescriptions:

2.1.1. Architecture

- The type of structure: multiple cable-stayed viaduct
- The positioning of the supports (piers and abutments)
- The continuity of the deck
- The external geometry of the piers and the pylons (forms and dimensions)
- The external geometry of the deck (cross-sectional form and dimensions)
- Other measures included in the architects report

2.1.2. Geometrical and functional data

- The alignment of the motorway
- The longitudinal profile
- The cross-sectional profile of the roadway on the structure

2.1.3. Technical matters

- A "useful project life" for the viaduct of 120 years
- The construction of the pier foundations on large-diameter shafts
- The fitting of wind screens in a transparent material
- Access to all interior parts of the structure
- The dimensions defined in Annexe 4 of the specification

2.2. Presentation of the project

2,460 m long, the Millau viaduct is a multi cable-stayed structure, slightly curved in plan on a radius of 20,000 m and with a constant upward slope of 3.025 % from north to south.

The structure is continuous along its eight cable-stayed spans; it consists of two end spans of 204 m each and six central spans of 342 m each.

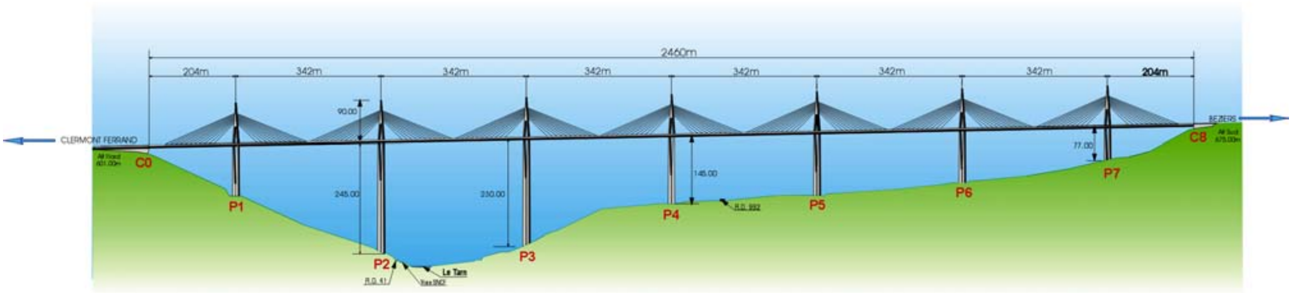


Figure 2: Elevation view of the viaduct

The cross-sectional profile of the motorway consists of a dual carriageway, each carriageway bordered by a 3 m emergency lane and a 1 m shoulder next to the central reservation. The width of the central reservation (4.45 m) has been determined by the size of the stay-cables, which are arranged in a single plane along the centre of the viaduct. The cross-sectional profile resulting from these constraints gives an overall deck width of 27.75 m.

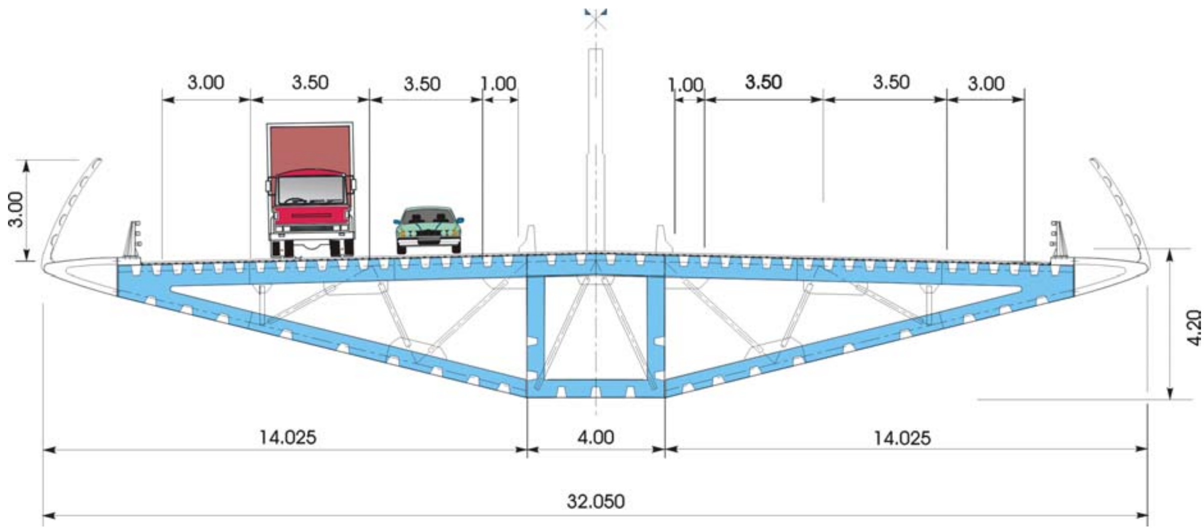


Figure 3: Functional cross-section of the deck

In addition, the structure is equipped with heavy-duty security barriers and screens to protect users against side winds.

The whole site is on rocks of the Secondary era composed of limestones, lime-rich marls and marls covered by fallen rocks and recent colluviums of variable thickness up to 10 m.

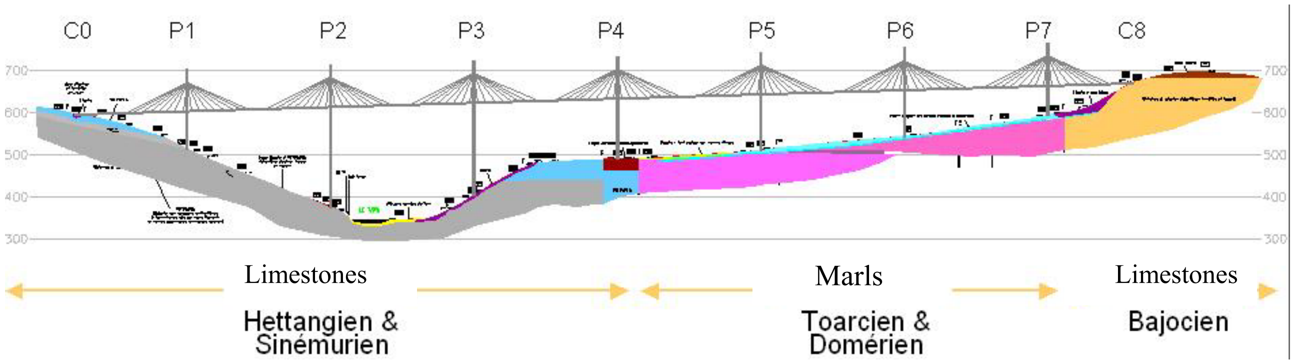


Figure 4: Geotechnical profile of the terrain encountered

The high complexity of the site, which makes access difficult to those areas with steep slopes, has led to the number of piers being limited and to their position being restricted to the top or bottom of the slopes.

The piers are presented in detail in another article for the Symposium. We simply mention here that the piers P2 (height 245 m) and P3 (height 223 m) are the two highest piers ever built in the world to date and that the top 90 m of the shafts of the piers are split into two.

The deck rests on each pier via four spherical bearings, two on each column half, thus effectively fixing the deck to the pier.

These characteristics make this structure the world record-holder for the longest multiple cable-stayed bridge with the stays arranged in a central plane over multiple spans as well as for the highest pier (pier P2).

➤ *Photo 2: Pier P2 (height 245 m)*

2.3. The static longitudinal scheme

The special structural feature of the viaduct is the fact that there are eight cable-stayed spans.

In a classic structure consisting of a single main cable-stayed span, the cable-stays anchored near the abutments or to small piers near the ends of the structure ensure that the top of the pylon is held firm.

In the case of the Millau viaduct, the flexibility of the adjoining spans means that this restraint is not provided and the head of the pylon is deflected towards the span that is loaded. The pylons and the piers thus contribute to the resistance of the structure to longitudinal bending. By fixing the deck to the piers (and the pylons) the rigidity of the structure is increased: the vertical movement is reduced in the loaded span and the forces transmitted to the adjacent spans are significantly reduced.

The dimensioning of the deck, in relation to its resistance and its deformability, is thus linked to the degree of flexibility of the piers and the pylons:

- With flexible piers and pylons it is necessary to design a deck that is rigid and thus thick
- With rigid piers and pylons, it is possible to have a deck with reduced inertia and thus less thick

In the case of the Millau viaduct, the scale of the effects due to the wind led to the adoption of the second solution, which allows the thickness of the deck to be reduced.

However, the fixing of the deck to piers that are very inflexible poses a problem in relation to temperature variations (and also to variations due to creep and shrinkage in the case of a concrete deck).

The maximum longitudinal displacement, which can reach 0.60 m at each end of the structure, generates, by deformation in the end piers, forces that are incompatible with their resistance capacity if those end piers are very rigid.

The solution chosen to ensure that the deck is fixed against rotation while giving the necessary horizontal flexibility compatible with the thermal dilation of the deck, was to split the shafts of the piers into two separate columns over the uppermost 90 m. The dimensions of the piers have, however, to remain large enough to avoid the risk of instability due to buckling.

Thus:

The doubling up of the number of bearings in the longitudinal sense ensures that bending of the structure is reduced to a minimum

The splitting of the pier shafts in to two, associated with their reduced inertia reduces the effects produced by thermal dilation of the deck.

For reasons of architectural homogeneity, the geometry of split shafts necessary for the end piers has been applied to all the piers (figure 5).

In the same way an inverted Y shape has been adopted for the pylons, which are metal, and which are oriented longitudinally as extensions of the split shafts of the piers. This arrangement gives the pylons the required high degree of rigidity (figure 6).

2.4. Cross-section of the deck

The deck consists of a trapezoidal profiled metal box girder with a maximum height of 4.20 m at the axis with an upper orthotropic decking made up of metal sheets 12-14 mm thick on the greater part of the main spans. To ensure resistance to fatigue, a thickness of 14 mm has been adopted for the whole length of the structure under the traffic lanes. This thickness is increased around the pylons.

The longitudinal stiffening of the upper orthotropic decking is provided by trapezoidal stiffeners 7 mm thick and in general 600 mm apart which go through the diaphragms.

The sloping base plates of the bottoms of the side box girders consist of 12mm sheet steel on the greater part of the spans, and 14-16 mm sheets around the pylons. 6 mm thick trapezoidal stiffeners are fitted at variable centres.

The bottom of the box girder consists of metal sheets of between 25 and 80 mm thick. Rigidity is provided by three trapezoidal stiffeners 14 or 16 mm thick.

Two vertical webs 4 m apart and consisting of metal sheet between 20 and 40 mm thick run the entire length of the structure in order to spread out the localised forces of the temporary piers during the launching of the deck. These webs are stiffened on their lower part by two longitudinal trapezoidal stiffeners.

The transverse stiffening of the deck is provided by lattice diaphragms at 4.17 m spacing on the spans.

The pylons are set into the deck:

- Longitudinally, continuity is ensured between the metal sheets of the webs of the central box girder and those of the walls of the pylons legs.
- Transversely, rigidity is provided by a frame which covers the bearings found on each pier shaft.

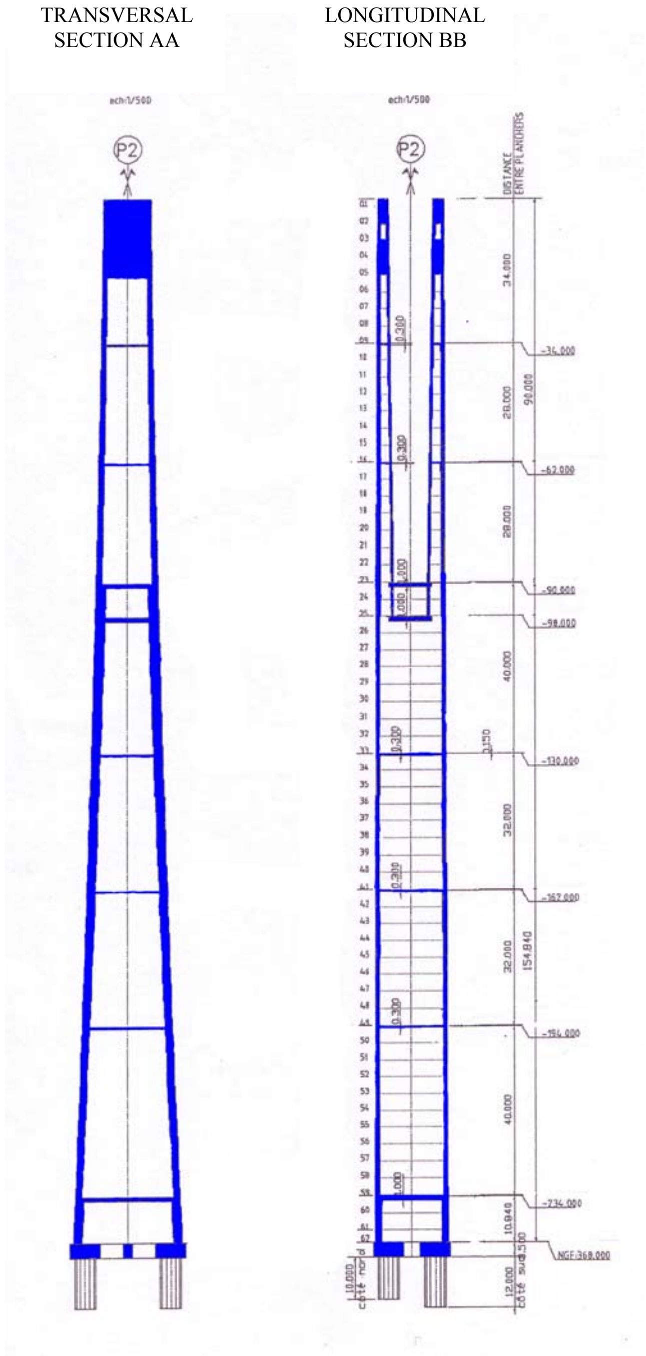


Figure 5: Formwork of pier P2

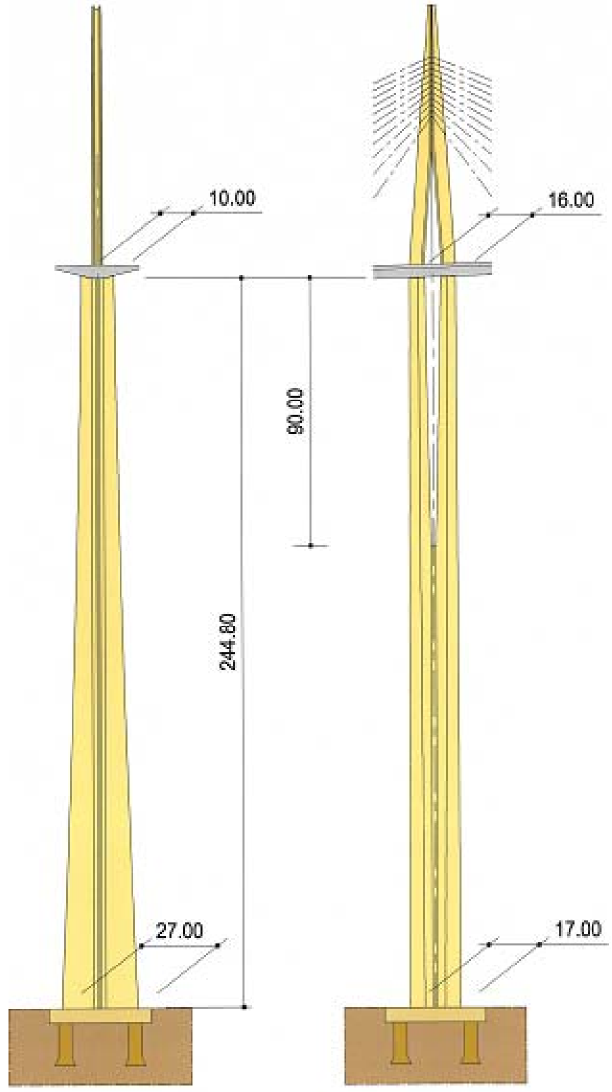


Figure 6: Elevation of a pier and pylon

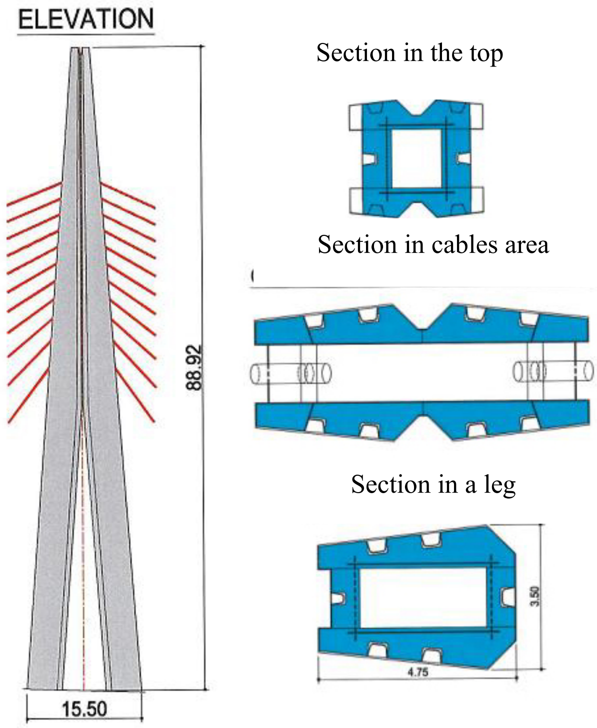
2.5. The pylons and the stay-cables

The legs of the pylons, which are 38 m high, are composed of two stiffened metal box girders.

These are surmounted by a mast 49 m high onto which the cables are anchored.

The top 17 m of each pylon, whose overall height is 87 m is not structural, but purely aesthetic.

The eleven pairs of cables which support each span are arranged in a single plane in a half-fan pattern. They are anchored along the axis of the central reservation at regular intervals of 12.51 m following the curvature of the structure.



The cables consist of T 15 strands of class 1,860 MPa which are super-galvanised, sheathed and waxed. Each cable is protected by a white, overall aerodynamic sheath made of non-injected PEHD.

This acts as a barrier to UV light and has discontinuous spirals on its surface in order to combat vibration resulting from the combined effects of wind and rain.

The number of strands making up each cable varies between 45 T 15s near the pylons and 91 T 15s towards the middle of each span.

The cable anchors are adjustable at the deck end and fixed on the pylons.

◄Figure 7: Geometry of a pylon

2.6. Wind studies

Since the viaduct is very high above the valley, the stresses generated by the effect of the wind are critical for the dimensioning of the structure.

Taking into account the latest knowledge on the subject, the very complete studies and trials conducted in the wind tunnel of the CSTB in Nantes were based on:

- An understanding of the characteristics of the wind at the site
- Determination of the wind model
- The aerodynamic behaviour of the different elements of the structure exposed to the wind: piers, deck, pylons and temporary piers
- Determination of the aerodynamic admittances both in bending and in drag from an aeroelastic trial on a model of the structure during its construction phase

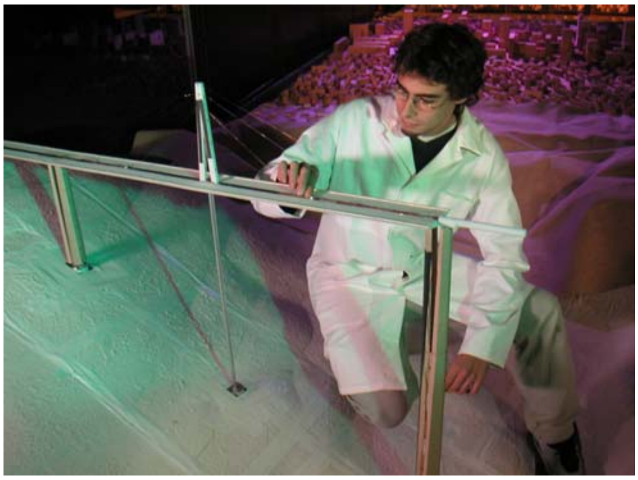


Photo 3: Aeroelastic trial of the construction phase of the pylon on the temporary pier Pi2 (photo CSTB)

- Determination of the torsional admittance of the deck from a trial on a cross-sectional model
- Trials to determine the efficiency and acoustic behaviour of the wind screen in PMMA
- Calculation of the stresses and movements in the structure
- Evaluation of the safety coefficients resulting from calculations based on extreme conditions under construction and in service.

The mean wind effects (by static calculation) and the effects of turbulence (by spectrum analysis) were calculated for different configurations, both for the construction and operational phases.

2.7. The choice of materials

The deck and the pylons, entirely of metal, are made of steels of grade S355 and S460.

The piers are constructed in B60 concrete. This concrete was chosen more for its durability than for its high mechanical resistance. The main objectives for the definition of the concretes were:

- Protection against alkaline reaction (level C)
- Protection against differential internal sulphate reactions
- Frost resistance according to the GRA 2002 rules
- Durability in relation to protection of the reinforcing material.

The other concrete elements of the structure: foundation shafts, abutments and foundation slabs are made of B35.

3. Construction of the viaduct

3.1. Organisation of the worksite

Work on the viaduct is being undertaken by companies from the EIFFAGE group: EIFFAGE TP for the civil engineering element and EIFFEL for the structural steel element; EIFFAGE TP is the main contractor for the group.

The worksite facilities are situated in four zones with a total area of approximately 8 ha.

In addition to these four main zones there are facilities with an average area of 3,500 m^2 at the foot of each support.

A visitor centre and car park have been constructed near the Cazalous worksite. By the end of December 2003 it had received over 220,000 visitors.

The construction of the viaduct has required the erection, under licence from the contracting authority, of:

- A bridge to cross the river Tarn between P2 and P3
- A temporary metal viaduct across the RD 992 Millau-Albi road near the Cazalous worksite.

The fact that the deck and pylons are constructed in steel, and that they are prefabricated elsewhere has significantly reduced the area of land required for construction of the viaduct.

The work carried out at the Millau site has thus been restricted to the construction of the piers and the abutments, the assembly of the pre-fabricated elements of the deck and pylons, and the installation of the deck by successive launching operations.

3.2. The foundations

From the geological point of view, the foundations rest on two main rock types:

- Limestones beneath the abutments C0 and C8 and beneath piers P1, P2, P3 and P4
- Marls beneath the other piers (P5, P6 and P7).

Each pier foundation slab rests on four foundation shafts 4.50 or 5 m in diameter and between 9 and 16 m deep.

The shafts of piers P4 to P7 are enlarged at the bottom to form an "elephant's foot".

The foundation slabs of the piers, whose thickness varies between 3 and 5 m, contain between 1,100 and 2,100 m^3 of concrete. The time taken to pour the concrete for the biggest slabs was 30 hours.

Photo 4: Concreting of the foundation base ➤

The slabs are made using B35 concrete with a minimum dose of CPA-CEM 1 52.5 PM ES – CP 2 cement at 280 kg/m^3.

3.3. The shafts of the piers

Each pier is treated as a worksite in its own right so that the construction of the seven piers requires seven completely independent worksites. On each pier a foreman directs a team of 12 people who work two 7-hour shifts.

Photo 5: General view of the pier worksites

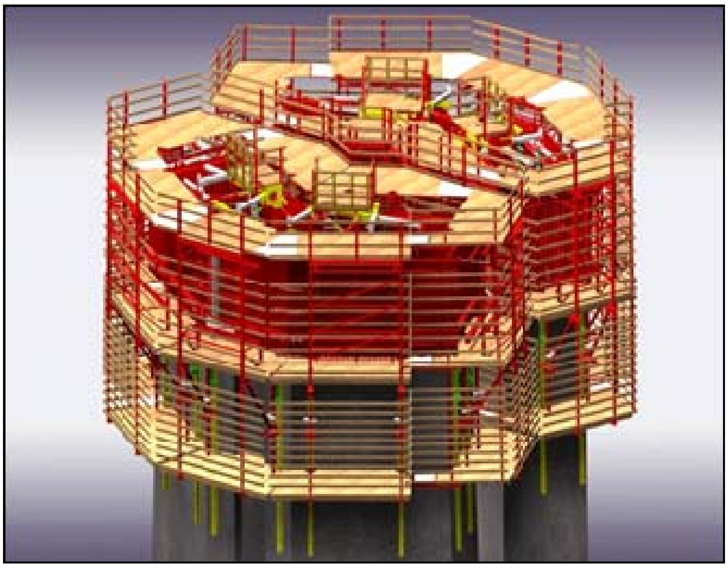


Photo 6: External formwork of the piers

The geometry of the piers varies from one pouring step to the next following a succession of skewed surfaces and angles, evolving in a practically imperceptible fashion and which required constant adaptation of the formwork.

The formwork was of the self-climbing type for the outer surfaces and crane-assisted for the inner surfaces. The height of each pouring step was 4 m.

The interior formwork units were designed in the form of classic systems raised by crane. In fact, the presence of intermediate slabs approximately every 30 m up the piers made the use of the more economical self-climbing technique impossible for the interior formwork.

A total of seven formwork systems were installed on the worksite. Altimetric checks by GPS ensured a precision of the order of 5mm in both X and Y directions.

The largest amount of concrete poured in one session was 322 m^3 for the first pouring step on P2, which lasted 12 hours. In the upper parts of the piers, the rate of concreting was 15 – 25 m^3/h.

The time required for each pouring step was three days for the single shafts and three to four days for the split shafts. The reinforcing assemblages were pre-fabricated on the ground, raised by crane and completed in place.

The decision to remove the formwork from the B60 concrete was taken on the basis of maturometer readings in order to guarantee a more or less constant equivalent age at the moment of removing the formwork.

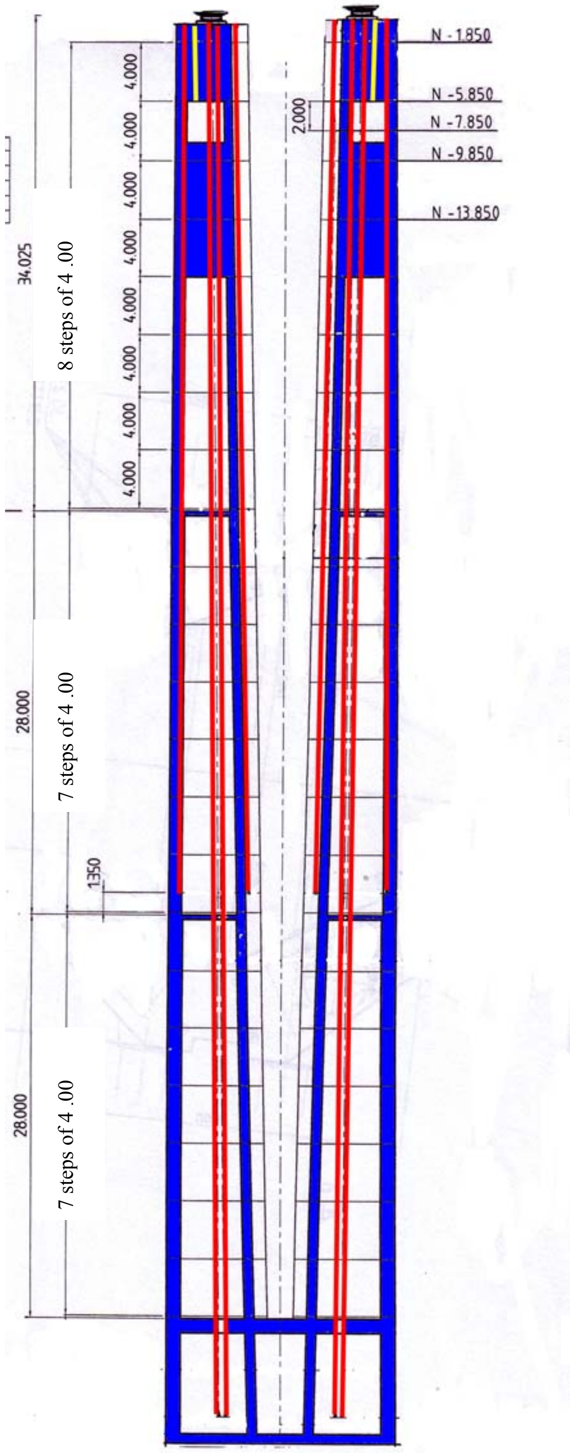
Since the piers of the Millau Viaduct were designed for a construction method different to that adopted by EIFFAGE, the design of the reinforcement system and the distribution of the forces on it at the tops of the piers was particularly complex.

Moreover, in the original design the split shafts were topped by a trimmer. This was subsequently removed from the design for aesthetic reasons, which made the installation of the equipment necessary for the launching of the deck particularly delicate.

For this reason the split shafts of the piers are solid for the top 17.85 m to allow the installation of the supports and the prestressing cables necessary to fix the deck to the pier.

The concrete of the shafts and the trimmer is a high-performance B60 0/14 dosed at 400 kg/m^3 of CPA – CEM I 52.5 PMES CP2 cement produced by two concrete plants with a nominal capacity of 80 m^3/h.

Photo 7: Head of a pier



3.4. The prestressing of the piers

Each split shaft is prestressed using eight 19 T 15 Super cables using the DYWIDAG procedure.

The sheaths are smooth tubes of steel with an internal diameter of 128 mm. The watertight joints between sections of sheath are made using thermoshrinkable sleeves.

Given the considerable length of the pre-stressing cables – around 100 m – an injection trial was undertaken over a great height with the aim of validating the methods and materials used on the viaduct. This trial was undertaken in the pier P3 of the Verrières viaduct, a structure situated on the A75 motorway a few kilometres north of the Millau viaduct. The trial consisted of injecting into a 110 m steel tube placed inside the pier.

This trial allowed the validation of the following:

- The composition of the grout used: SUPERSTRESSCEM SPA CEM I 42.5 PMES CP2
- The duration of the injection
- The efficiency of the equipment
- The procedures used

The original design did not allow for pre-stressing of the piers, so its use in the actual construction will improve the durability of the structure.

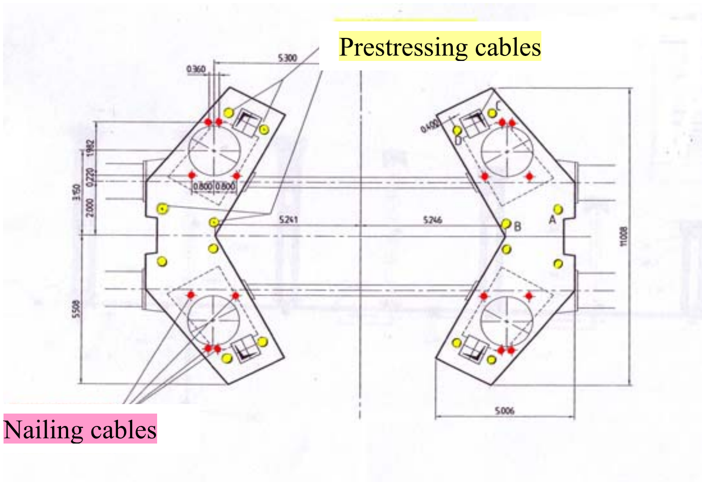


Figure 8: Prestressing of piers: elevation and cross-section

3.5. The abutments

At 13 m wide, the hollow abutments are narrower than the deck. Fitted with lateral cantilevers, they extend the shape of the deck up to the point where it meets the natural ground.

The concrete for the two abutments C0 and C8 was poured in several stages because of their considerable height and length.

The abutment C0, the closest to the planned toll station, houses the equipment and services necessary for the operation of the viaduct.

Those parts of the abutments exposed to splashing by de-icing salt (the only load-bearing structures so exposed) are constructed with a concrete "G + S" conforming to the standards known as "GRA". This type of concrete, with an air-entraining agent, was chosen for its capacity to withstand this type of attack.

The concrete used is type B 35G 0/14 with a minimum dose of 385 kg/m3 of cement CPA CEM I 52.5 PMES CP2.

3.6. The temporary piers

The installation of the deck by successive launching operations requires the erection of seven temporary piers. These piers consist of a metal framework in the form of a K with a square section of 12 m x 12 m whose members are tubes of 1,016 mm diameter.

Photo 8: Docking of the deck on the temporary support Pi2 (height 173 m)

The temporary piers are put in place by telescoping, apart from those for the two end spans which, owing to their small size (less than 30 m high), were lifted directly into place by crane.

The top of each temporary pier is fitted with a metal trimmer to receive the launching supports, known as translators, as well as the work platforms.

The highest temporary pier is 173 m high.

Up to 140 m, The telescoping can be carried out at a wind speed of up to 72 km/h. The last 30 m must be telescoped at wind speeds below 50 km/h. The speed of telescoping has reached 12 m per day.

3.7. The construction of the deck

3.7.1. The pre-fabrication of the deck in the factory

The cross-sectional profile of the deck has been designed by EIFFEL to take account of the possibility of pre-fabrication in the factory, transport, on-site assembly and launching.

The main part of the deck is thus transported to the site in the form of "kits" consisting of:

- The central box girder, 4 m wide and 4.20 m high
- Stiffened intermediate panels (upper and lower plates) from 3.75 to 4.20 m
- The two extremities of the side girders of 3.84 m
- Brackets in UPN making up the transverse diaphragm of the girder

The principle of the deck construction is as follows:

- Fabrication of the elements of the central box girder 1, 8, 9 and 10 and the decking elements 2, 3, 6 and 7 and the lateral box girders 4 in the EIFFEL factory at Lauterbourg,

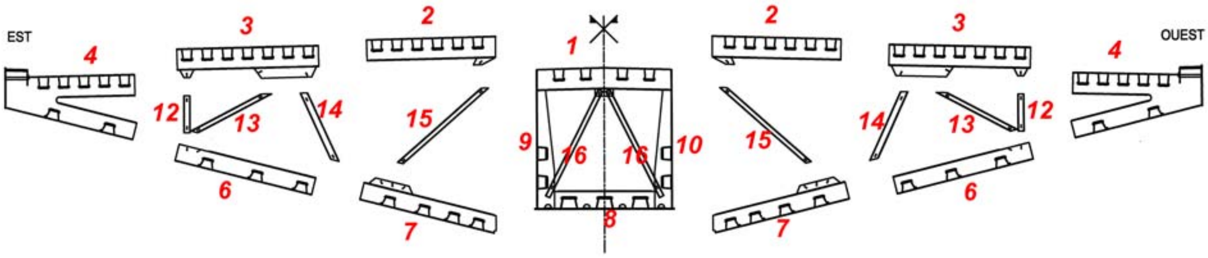


Figure 9: Cross-sectional exploded view of the deck

- Transport from the factory at Lauterbourg,
    - For the decking elements 2, 3, 6 and 7 and the extremities of the lateral box girders 4: directly to the site at Millau,
    - For the elements of the central box girders 1, 8, 9 and 10: to the EIFFEL factory at Fos-sur-Mer,
- Assembly of the central box girders at Fos-sur-Mer,
- Transport of the central box girders from Fos-sur-Mer to Millau.

In order to allow the Lauterbourg factory to produce all 2,078 decking elements by the beginning of 2004, EIFFEL invested in some very high technology equipment:

- A plasma gas-cutting machine which allows the temperature of the flame-oxygen mixture to reach 28,000°C very quickly thanks to the injection of plasma into the mixture. The cutting torch thus obtained can cut 1.80 m of steel per minute with extreme precision
- A two-headed welding robot
- A 160-tonne auto-lifting trailer
- Automatic laser tacheometers to check the dimensions of the decking

Photo 9: Welding robot

The elements of the viaduct are delivered to site by road convoys which will number around 2,000 by the time the structure is complete.

The 173 central box girders arrive in pieces at the EIFFEL factory at Fos-sur-Mer. They are stored outside prior to being assembled on two special frames.

Once a central box girder has been assembled at Fos-sur-Mer, it is transported to the Millau worksite in units of 15 to 22 m long with a maximum weight of 90 tonnes at the rate of three units per week.

The elements of the lateral girders of the deck are transported to the site in pieces 20 – 24 m long with a maximum weight of 40 tonnes.

3.7.2. Assembly of the deck on-site

Two on-site factories have been set up on the platforms behind each abutment with all the necessary equipment (cranes, 90-tonne material-handling gantries, welding shops, paint shops).

Each factory consists of three work zones 171 m long, each with its own specific activities:

- The first zone, farthest from the abutment, is for joining together the pieces of box girder
- The second zone is used to assemble the other elements of the deck and to join them to the central girder
- The third zone is where the completely-assembled deck is painted, and where the BN4s, the mouldings and the uprights of the wind screen with their protective mesh are assembled

The welding work on the site necessitates about 75 welders for each assembly area.

The complete assembly of a 171 m deck section requires the use of approximately five tonnes of brazing metal and the time taken has been reduced to approximately four weeks since the fifth launching.

The total consumption of brazing metal for the whole structure is estimated at 150 tonnes.

Photo 10: Area for prefabrication of the deck – south side

3.8. Launching the deck

The metal deck is put in position by launching consecutive sections of 171 m as they are ready (figure 10). Each launch operation consists of moving the leading edge of the deck over the 171 m which separates each support (pier or temporary pier) from the next.

At the southern end, where 1,743 m of deck is required, the first launch took place at the end of February 2003. The first launch with the pylon Py3 cable-stayed in position took place at the beginning of July 2003. The launch L4S, for which it was necessary to re-tension the cable stays, took place at the end of August 2003 (photo 11). At the end of 2003, seven launches out of a total of twelve had taken place.

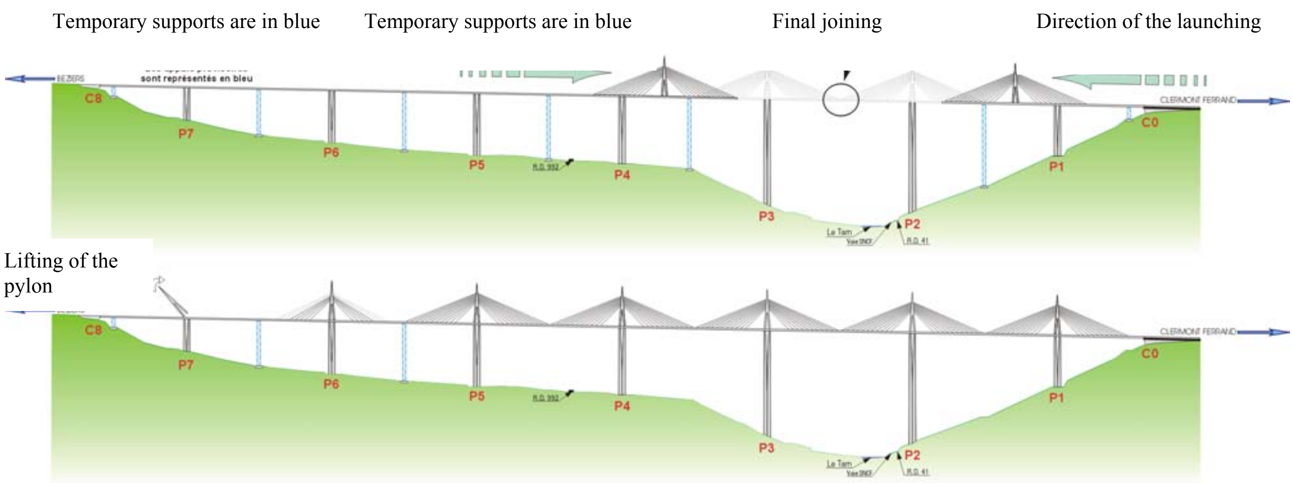


Figure 10: Construction of the deck and the pylons

Photo 11: Launch L4S after re-tensioning of the stay cables

Since the summer of 2003, identical operations have taken place at the northern end where there are 717 m of deck to be constructed. At the end of 2003, three out of the six required launches had taken place.

The final joining of the two parts of the deck is planned for the beginning of June of 2004.

The top of each pier is equipped with a metal trimmer on which the launching system, consisting of four equilibrium devices and four translators, is arranged, each system being placed transversely below the webs and at 21 m apart in the longitudinal sense.

During the launch, the jacks of the two cradles installed beneath the same web are hydraulically linked to ensure equality of pressure in all the jacks and thus to allow variations in longitudinal rotation of the deck (bogie effect).

Each cradle is equipped with a translator, a system consisting of a horizontal "lifting" jack, capable of producing a force of 250 tonnes and two horizontal jacks of 60 tonnes which retract to allow the deck to move a distance of 600 mm.

Each translator consists of a U-shaped cradle in which a lifting wedge moves under the force of the lifting jack, and a runner moved by the two horizontal launching jacks. It rests on a set of four or six simple action jacks which can be locked by nuts.

Each launch cycle allows the deck to be moved 600 mm and lasts four minutes on average.

Photo 12: Deck launching system

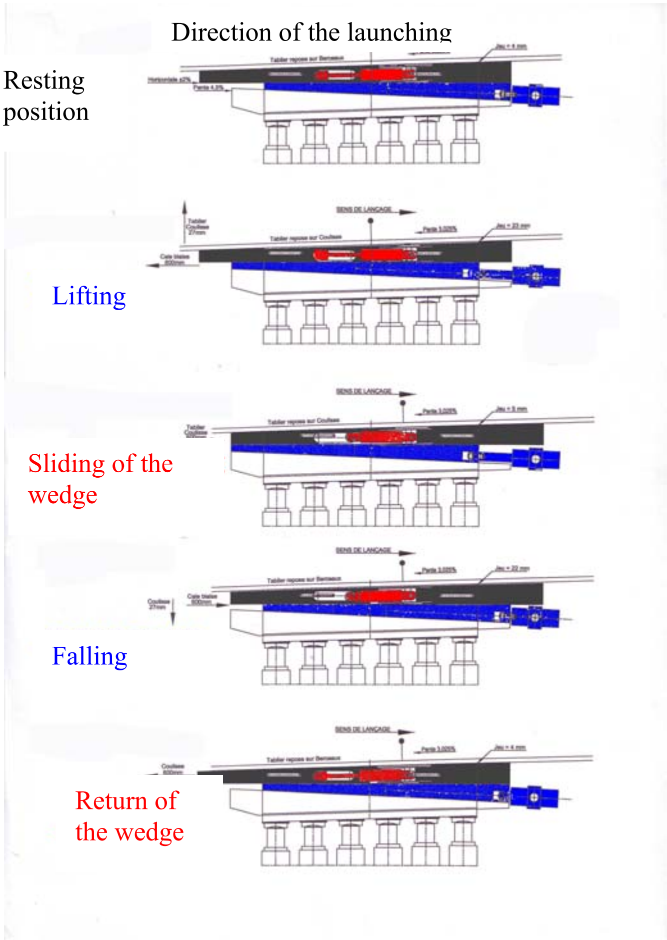


Figure 11: Principal of translation of the deck

The principle of the translation of the deck is as follows:

1. In its initial resting position, the deck is supported by the cradle
2. The lifting jack, by making the wedge slide, lifts the deck from its support and leaves it resting on the runner
3. The rails which carry the deck then move forward under the force of the horizontal launching jacks
4. Once the 600 mm of movement has been carried out, the wedge resumes its initial position, leaving the deck resting on the cradle.

All the translation systems are centrally controlled, and hydraulic power units with a controlled flow rate guarantee that each translator moves over an identical distance.

The hydraulic power units that have been installed allow a mean overall launch rate of 10 m/h, in other words 16 cycles per hour.

The launching of the deck from each abutment is carried out using one cable-stayed pylon to prevent the overhang of the leading section from dropping down. The length of this leading section (171 m) corresponds to the distance between one support (pier or temporary pier) and the next.

During the launching, the tension in these stay cables (twelve in total out of the twenty two which will eventually be attached to each pylon) varies continuously depending on the position of the pylon.

To prevent possible vibrations in the stay cables, which are only lightly tensioned, temporary perpendicular cables are fitted, which, apart from their slight dampening effect, increase the frequency of vibration of the stay cables themselves by making them more rigid.

The leading extremity of the overhanging section of the deck is fitted with a nose whose purpose stabilise the leading edge in case of an emergency stop in the launch owing to high wind and to facilitate docking onto the different supports.

Photo 13: Nose fitted to the leading edge of the deck

One of the original construction ideas proposed by the consultants Greisch was to take advantage of the flexibility of the deck to carry out a launch with a double curve.

Photo 14: Deck during launching – south side

On the supports P2 to P6, and on the temporary piers Pi2 to Pi6, the level of the launch profile is the final level of the supports. On the other hand, behind the abutments C0 and C8, the launch supports are 5.40 m above the final level of the structure for supports N1 and S1 and 4.80 m for the others.

The adjustment of the levels is achieved by a longitudinal double curve, the supports on which the deck slides being raised by 4.40 m on C0 and C8, by 3.50 m on Pi1 and Pi7 and by 0.30 m on P1 and P7.

The launching operations take place under constant meteorological surveillance with a maximum wind speed of 85 km/h.

In the stationary phases between launches, the structure is able to withstand turbulent winds whose speed is equal to 90 % of the design wind speed for when the structure is operational, i.e. gusts of 185 km/h.

The stationary phases correspond systematically with a position where both the leading edge of the deck and the centre of the pylon are directly over a pier or a temporary support.

3.9. Final joining up of the two deck halves

After the last launch, the two parts of the deck will be joined together 270 m above the Tarn valley. This operation, which will be carried out under meteorological surveillance, consists of welding together the leading edges of the northern and southern deck sections in order to ensure continuity between them.

3.10. Erection of the pylons and the end of the construction phase

The metal pylons are constructed in the Frouard factory of Munch, a subsidiary of Eiffel.

The elements of each pylon are made in the factory on the same principle as those of the deck and then delivered to the worksite by road in units of less than 12 m in length. The maximum weight of one unit is 75 tonnes.

The construction method used for the two launch pylons Py2 and Py3 is different to that used for the other pylons, erected after the joining of the deck halves.

The elements of the launch pylons Py2 and Py3 are pre-assembled on the ground, then placed on the deck using an 850-tonne tracked crane.

The upper elements, or "caps", of pylons Py2 and Py3, which are 17 m long, will be fitted after the joining together of the two halves of the deck just after the last launch.

After the northern and southern deck sections have been joined, the five remaining pylons, Py1 and Py4 to Py7, each weighing 650 tonnes will be assembled on the ground behind the abutments. Placed on multi-axle transporters, they will be moved to their places above the piers and lifted into their final position by two metal lattice towers.

Photo 15: Lifting into position by crane of the elements of a launch pylon

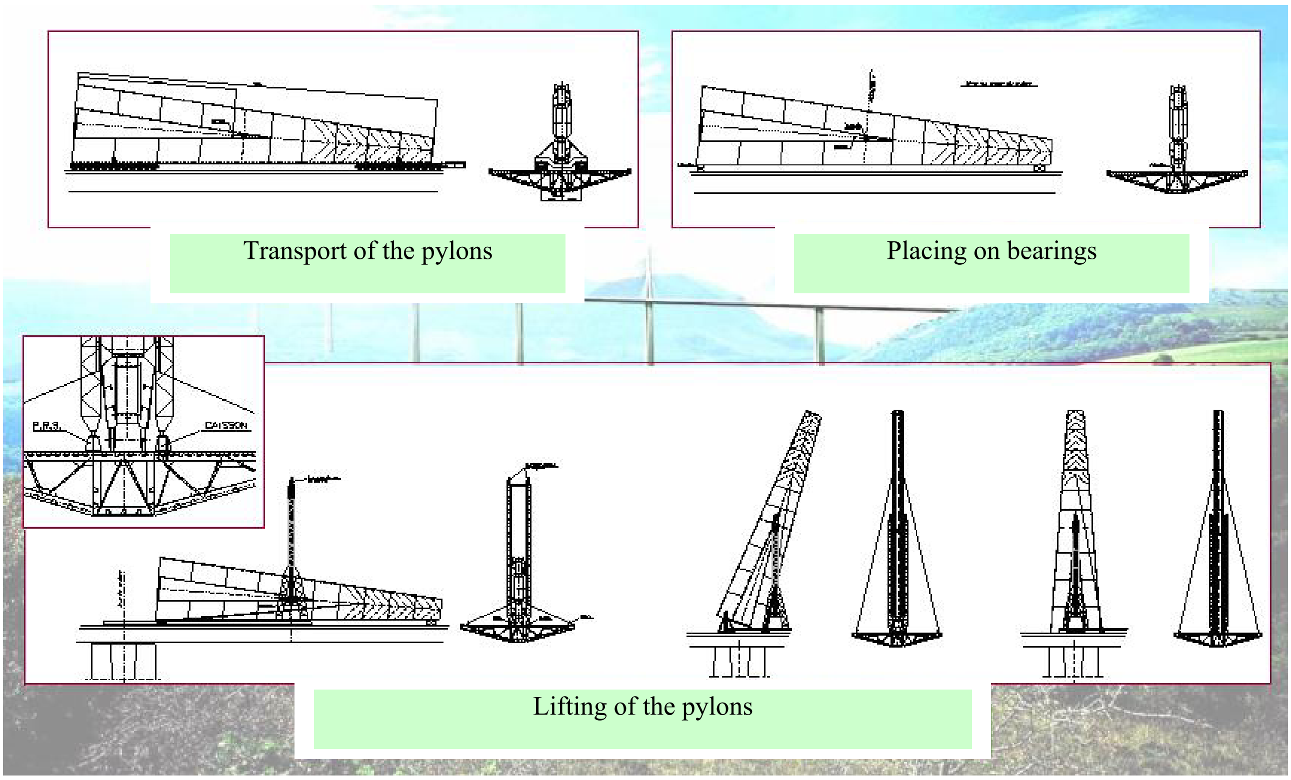


Figure 12: Transport and lifting of the pylons

It will then remain to fit and adjust the cable-stays, install the equipment and put on the road surface, not forgetting the dismantling of all the launching accessories (temporary piers, trimmers at the tops of the piers, launch rails).

3.11. Trials and Tests

As well as geotechnical trials, wind trials and all the normal trials required to meet materials and equipment standards, a certain number of trials are being undertaken in order to validate the design and to ensure that the required level of quality is achieved in relation to the "useful project life" of the viaduct of 120 years.

Among the numerous trials conducted the following may be cited:

- Creep and shrinkage tests on the B60 concrete of the piers
- Durability tests on the concrete: permeability, porosity, coefficient of chloride diffusion, resistance to freeze-thawing and to de-icing salt, moisture expansion
- Tests on the aging of the reinforced concrete by destructive checks (carbonation, chloride penetration) on blocks exposed to the same environmental conditions as the viaduct
- Trials on the cable-stays: fatigue, watertightness of different components
- Friction trials on the DUB material used for the spherical bearings on the piers and for the MSM material used for the sliding supports for the launching
- Accreditation trial for the system developed by APPIA for ensuring watertightness and the quality of the road surfacing material
- Static and dynamic load trials prior to handover of the structure.

3.12. Instrumentation and monitoring of the structure during construction

In order to verify the calculations and to be able to judge the behaviour of the structure during construction, in particular during launching operations, an instrumentation programme has been put in place, considerably more thorough than would normally be the case for a cable-stayed structure. This programme allows monitoring of the behaviour of all elements of the structure during construction (foundation shafts, foundation slabs, piers, temporary piers, deck, pylons, stay-cables).

Thus there are in place:

- Measures to check the construction itself

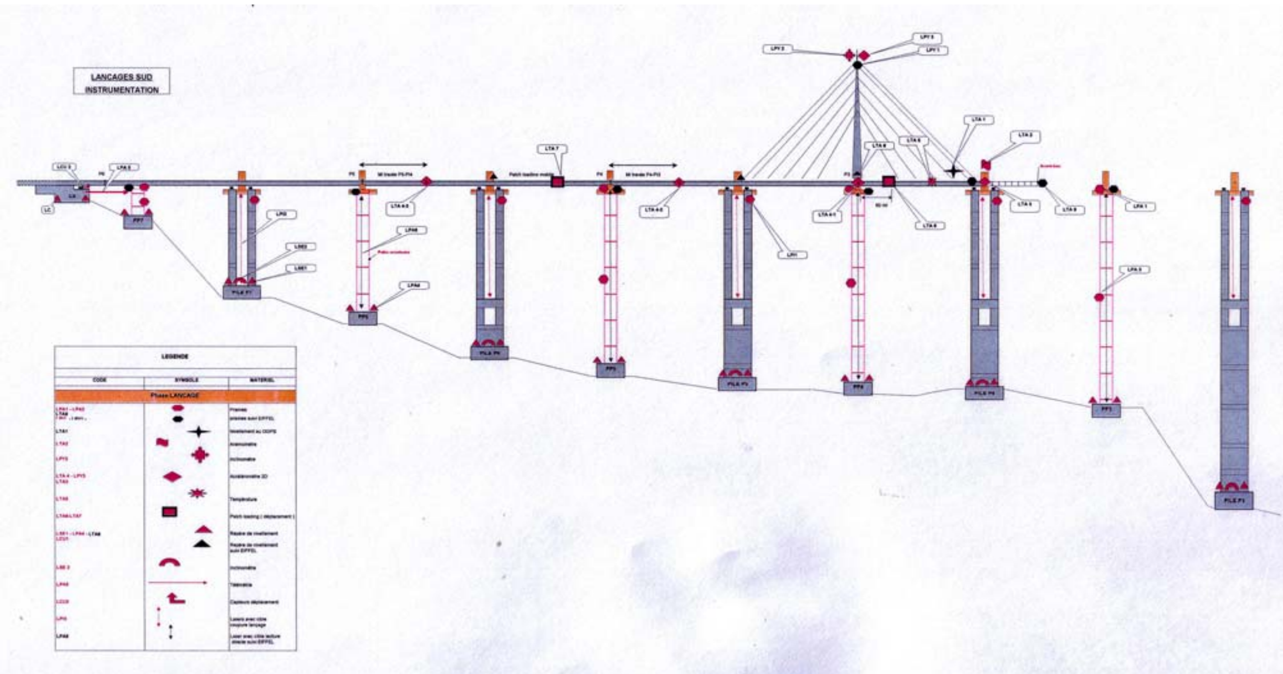


Figure 13: Instrumentation of the viaduct under construction

- Measures to verify the behaviour of the structure during launching

Photo 16: Checking "patch-loading" during a launch

The operations associated with the official handover of the structure will enable baselines to be established which will subsequently act as references for the later monitoring of the structure during its operation.

4. Organisation of technical studies

The technical studies for the civil engineering aspects of the project were carried out under the direction and co-ordination of the technical department at the worksite by the design department of_Eiffage TP (STOA) and the consultants EEG-Simecsol (and the sub-contractors Thalès and Serf).

The technical studies for the steel structure aspects of the project were carried out by the company Greisch Engineering of Liège (Belgium).

The surveys were checked by Setec TPI, the project manager's external auditing office.

The technical studies, which involved the preparation of more than 500 technical notes and calculations and 4,000 plans, required teams of up to 60 people at the peak period, of whom about 25 were engineers and 35 were design technicians. The main phase of the studies lasted approximately eighteen months.

The arbitration of differences which arise between the project manager and the company is the role of the project owner (CEVM) which has assembled a panel of independent experts. The project owner has thus formed a technical committee consisting of top-level engineers from the project manager, the company and independent experts.

The experts for the project owner are Michel Virlogeux for the overall design and wind studies, Jean-Claude Foucriat and J. Piccardi for problems relating to the steel structure and François Schlosser for geotechnical problems.

The project owner has an external audit carried out every six months by an organisation (AFAQ) approved by the contracting authority (the State).

Photo 17: Firework display marking the end of the construction of the piers

THE MAIN PARTICIPANTS

Contracting authority	The French State represented by RCA and AIOA
Project owner	Compagnie Eiffage du Viaduc de Millau
Project manager	Setec – Sncf group
Civil engineering company	Eiffage TP (main contractor)
Structural steel company	Eiffel Construction Métallique
Construction survey design teams	
	Civil engineering: Stoa Eiffage TP and EEG-Simecsol (+ Thales – Serf)
	Structural steel: Greisch Engineering
Architect	Lord Norman Foster's practice
Experts for the project owner	J. Foucriat, J. Piccardi, F. Schlosser, M. Virlogeux

THE MAIN QUANTITIES

Earthworks	**Platforms**	350,000 m^3
Civil engineering	**Foundation shafts**	
	• concrete	6,000 m^3
	• passive reinforcing	1,200 tonnes
	Foundation slabs	
	• concrete	13,000 m^3
	• passive reinforcing	1,300 tonnes
	Piers	
	• concrete	53,000 m^3
	• passive reinforcing	10,000 tonnes
	• pre-stressed reinforcing	200 tonnes
	Abutments	
	• concrete	5,500 m^3
	• passive reinforcing	550 tonnes
	Temporary piers	
	• concrete	7,500 m^3
	• passive reinforcing	400 tonnes
Structural steel	**Deck**	
	• S 355 steels	23,500 tonnes
	• S 460 steels	12,500 tonnes
	Pylons	
	• S 355 steels	3,200 tonnes
	• S 460 steels	1,400 tonnes
	Stay-cables	1,500 tonnes
	Temporary piers and metal trimmers	
	• S 355 steels	3,200 tonnes
	• S 460 steels	3,200 tonnes
	Telescoping cage	400 tonnes