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Design Practice in Europe

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64.1 Introduction

Europe is one of the birthplaces of bridge design and technology, beginning with masonry bridges and aqueducts built under the Roman Empire throughout Europe. The Middle Ages also produced many innovative bridges. The modern role of the engineer in bridge design appeared in France in the 18th century. The first bridge made of cast iron was built in England at the end of the same century. Prestressed concrete was born in France before extending throughout the world. Cantilever construction and incremental launching of concrete decks were devised in Germany, as well as modern cable-stayed bridges. The streamlined box-girder deck for long-span suspension bridges was born in England. The variety of bridges in Europe is enormous, from the point of view of both their age and their type.

Outstanding works of bridge history in Europe can be presented as follows.

Bridge	Year	Country	Designer	Comments
Unknown	600 B.C.	I	Etruscans	Probable use of vaults for bridge construction
Gardon River Bridge *	13 B.C.	F	Romans	Aqueduct 49 m high, with three rows of superposed arches
Céret Bridge over the River Tech	1339	F	Unknown	Masonry bridge spanning 42 m
Wettingen Bridge	1764	CH	Johann Ulrich Grubenmann	Biggest wooden bridge in Europe with a 61 m span
Coalbrookdale Bridge	1779	GB	Abraham Darby III	First metallic bridge: cast iron structure
Sunderland Bridge	1796	GB	Rowland Burdon	Six cast iron arches, each made up of 105 segments
Saint-Antoine Bridge	1823	CH	Guillaume Henri Dufour	First permanent suspension bridge with metallic cables in the world
Britannia Bridge	1850	GB	Robert Stephenson	First tubular straight girder, spanning 140 m, consisting of wrought iron sheets
Crumlin Viaduct	1857	GB	Charles Liddell	First metallic truss girder viaduct
Bridge over the River Isar	1857	D	Von Pauli, Gerber, Werder	Welded and bolted iron truss girder
Royal Albert Bridge	1859	GB	Isambard Kingdom Brunel	Metal truss girder, first of a whole modern generation of railway bridges
Maria Pia Bridge over the River Douro	1877	P	Gustave Eiffel	Arch spanning 160 m, made up of metal structure
Antoinette Bridge	1884	F	Paul Séjourné	Culmination of masonry bridges
Firth of Forth Bridge *	1890	GB	Sir John Fowler and Sir Benjamin Baker	First large steel bridge in the world — two main spans 520 m long
Alexandre III Bridge *	1900	F	Jean Résal	15 very slender arches composed of molded steel segments
Salginatobel Bridge	1930	CH	Robert Maillard	Arch marking the concrete box-girder birth
Albert Louppe Bridge *	1930	F	Eugène Freyssinet	Three reinforced concrete vaults, each spanning 188 m — wooden formwork spanning 170 m
Linz Bridge over the River Danube	1938	AUT	A. Sarlay and R. Riedl	First welded girder 250 m long — three spans
Luzancy Bridge	1946	F	Eugène Freyssinet	Concrete bridge prestressed in three directions, made up of precast segments
Cologne Deutz Bridge	1948	D	Fritz Leonhardt	Composite steel plate-concrete box-girder bridge spanning 184 m
Percha Bridge	1949	D	Dyckerhoff and Widmann	First reinforced concrete large span cantilever construction
Donzère Mondragon Bridge	1952	F	Albert Caquot	First cable-stayed bridge — 81 m long main span
Düsseldorf Northern Bridge	1957	D	Fritz Leonhardt	First modern cable-stayed metallic bridge
Bendorf Bridge *	1964	D	Ulrich Finsterwalder	Cast-in-place balanced cantilever girder bridge — 208 m long main span
Choisy Bridge	1965	F	Jean Muller	First prestressed concrete bridge consisting of precast segments with match-cast epoxy joints
First Severn Bridge *	1966	GB	William Brown	Decisive stage: deck aerodynamic study in a low- and high-speed wind tunnel
Weitingen Viaduct	1975	D	Fritz Leonhardt	Steel span world record: 263-m-long span
Saint-Nazaire Bridge	1975	F	Jean-Claude Foucriat	Steel cable-stayed bridge world record — 400-m-long main span
Brotonne Bridge	1977	F	Jean Muller	Prestressed concrete cable-stayed bridge world record — 320-m-long main span
Kirk Bridge	1980	Croatie	Ilija Stojadinovic	World record — prestressed concrete arch spanning 390 m
Ganter Bridge	1980	CH	Christian Menn	174-m-long cable stayed span — stay planes protected by concrete walls
Normandie Bridge *	1995	F	Michel Virlogeux	World record — cable-stayed bridge with a 856-m-long main span
Storebaelt Bridge *	1998	DK	Cowi Consult	6.6- and 6.8-km-long bridges including a suspension bridge with a 1624-m long central span
Tagus Bridge	1998	P	Campenon Bernard	13-km-long bridge including a cable-stayed bridge with a 420-m-long main span
Gibraltar Straight Bridge	Project	E	Not yet known	Suspension bridge: 3.5- to 5-km long main spans
Messina Straight Bridge	Project	I	Not yet known	Suspension bridge: 3.3-km-long main span

* A brief description of these bridges are given later with a photograph.

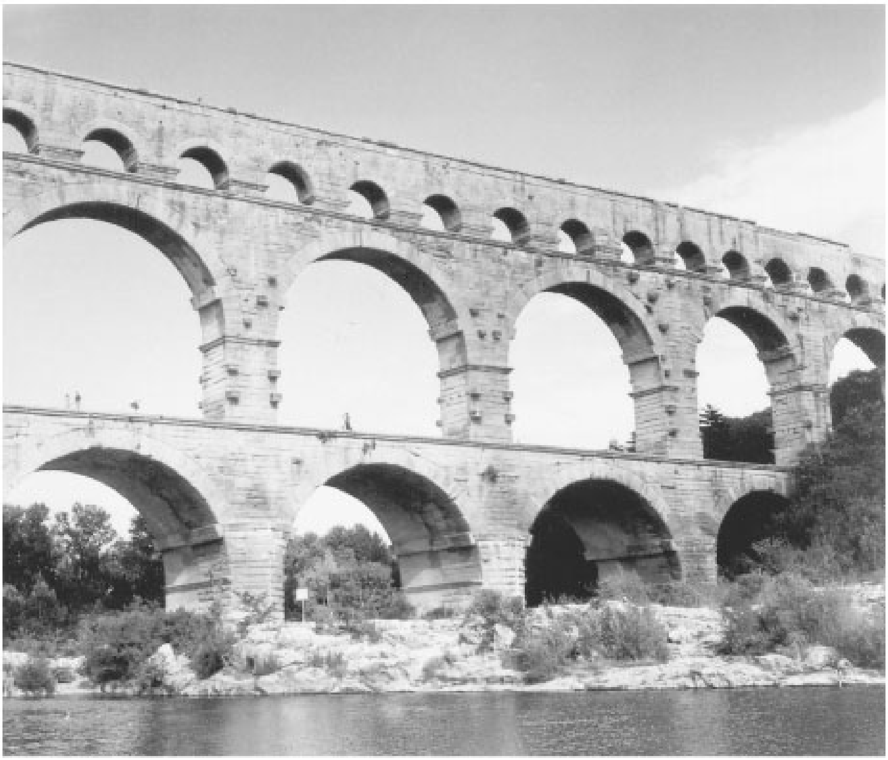

FIGURE 64.1 Gard Bridge over the River Gardon. (*Source*: Leonhardt, F., Ponts/Puentes — 1986 Presses Polytechniques Romandes. With permission.)

If we could choose only eight outstanding bridges, they would be as follows.

1. *Gardon River Bridge* (*13* B.C.) — The Gardon River Bridge, also named Gard bridge, located in France, is an aqueduct consisting of three rows of superposed arches, composed of big blocks of stone assembled without mortar. Its total length is 360 m, and its main arches are 23 m long between pillar axes. It fully symbolizes Roman engineering expertise from 50 B.C. to 50 A.D. (Figure 64.1). Built with large rectangular stones, the bridge surprises by its architectural simplicity. Repetitivity, symmetry, proportions, solidity reach perfection, although the overall impression is that this work is lacking spirit.
2. *Firth of Forth Bridge* (*1890*) — The Forth Railway Bridge, located in Scotland, Great Britain, was the first large steel bridge built in the world. Its gigantic girder span of 521 m, longer than the main span length of the greatest suspension bridges of the time, made this bridge a technical achievement (Figure 64.2). In all, 55,000 tons of steel and 6,500,000 rivets were necessary to build this structure costing more than 3 million sterling pounds. The very strong stiff structure, made of riveted tubes connected at nodes, consists of three balanced slanting elements and two suspended spans, with two approach spans formed of truss girders. The total bridge length is 2.5 km.
3. *Alexandre III Bridge* (*1900*) — This roadway bridge over the River Seine in Paris, France, designed by Jean Résal, bears on 15 parallel arches made up of molded steel segments assembled by bolts. These arches are rather shallow, the ratio is $1/17$, and so, massive abutments are necessary. The River Seine is crossed by a single span, 107 m long; the bridge deck is 40 m wide (Figure 64.3).
4. *Albert Louppe Bridge* (*1930*) — This bridge, located in France, is the most beautiful expression of Eugène Freyssinet's reinforced concrete works. The three arches, each spanning 186.40 m

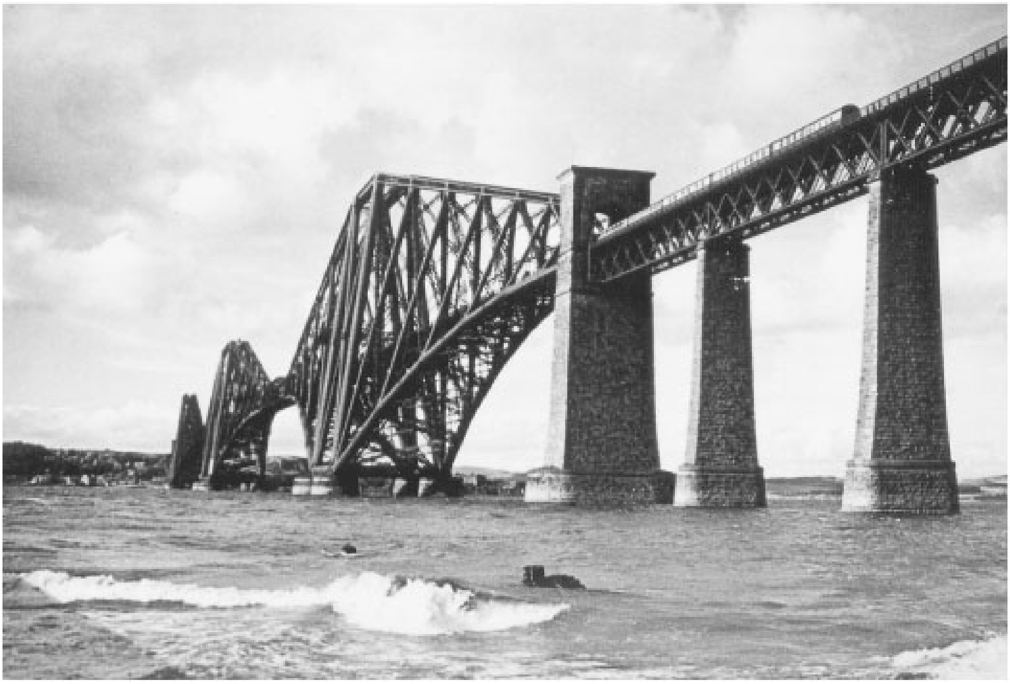

FIGURE 64.2 Firth of Forth Bridge. (Courtesy of J. Arthur Dixon.)

FIGURE 64.3 Alexandre III Bridge. (Courtesy of SETRA.)

(Figure 64.4) crossed the River Elorn for half the cost of a conventional metal bridge. The arches are three cell box girders, 9.50 m wide and 5.00 m deep on average. The deck is a girder with reinforced concrete truss webs. The formwork used for casting the three vaults, moved on two 35 by 8 m reinforced concrete barges, was the greatest and the most daring wooden structure in construction history with its 10-m-wide huge vault spanning 170 m.

FIGURE 64.4 Albert Louppe Bridge. (Courtesy of Jean Muller International.)

5. *Bendorf Bridge* (*1964*) — Built in 1964 near Koblenz, Germany, this structure has a total length of 1029.7 m with a navigation span 208 m long over the River Rhine. Designed by Ulrich Finsterwalder, it is an early and outstanding example of the cast-in-place balanced cantilever bridge (Figure 64.5). The continuous seven-span main river structure consists of twin independent single-cell box girders. Total width of the bridge cross section is 30.86 m. Girder depth is 10.45 m at the pier and 4.4 m at midspan. The main navigation span has a hinge at midspan, and the superstructure is cast monolithically with the main piers. The structure is three-dimensionally prestressed.
6. *First Severn Bridge* (*1966*) — The suspension bridge over the River Severn, Wales, Great Britain, designed and constructed in 1966, marks a distinct change in suspension bridge shape during the second half of the 20th century (Figure 64.6). William Brown, the main design engineer, created a 988-m-long central span. The deck is a stiff and streamlined box girder. Its aerodynamic stability was improved in a wind tunnel, with high-speed wind tests under compressed airflow. Since the opening of the bridge, many designers have been drawn from afar to its shape, new at the time, but now looked upon as classical.
7. *Normandie Bridge* (*1995*) — The cable-stayed bridge, crossing the River Seine near its mouth, in northern France, is 2140 m long. Its 856-m-long main span constitutes a world record for this kind of structure, although the bridge in principle does not bring much innovation in comparison with the Brotonne bridge from which it is derived (Figure 64.7). The central 624 m of the main span is made of steel, whereas the rest of the deck is made of prestressed concrete. The deck is designed specially to reduce the impact of wind blowing at 180 km/h. Reversed Y-shaped pylons are 200 m high. The stays, whose lengths vary from 100 to 440 m, have been the subject of an advanced aerodynamic study because they represent 60% of the bridge area on which the wind is applied.

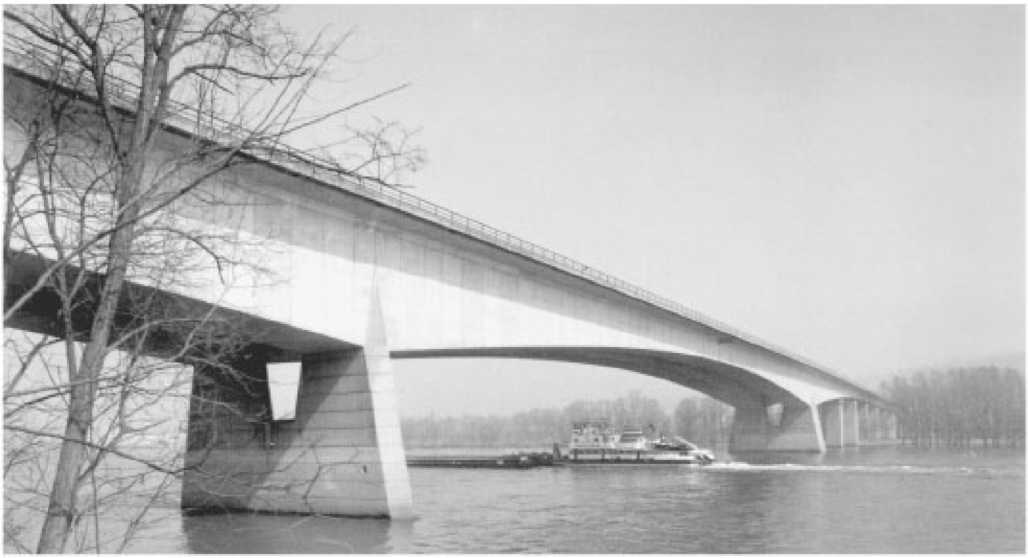

FIGURE 64.5 Bendorf Bridge. (*Source*: Leonhardt, F., Ponts/Puentes — 1986 Presses Polytechniques Romandes. With permission.)

FIGURE 64.6 First Severn Bridge. (*Source*: Leonhardt, F., Ponts/Puentes — 1986 Presses Polytechniques Romandes. With permission.)

FIGURE 64.7 Normandie Bridge. (Courtesy of Campenon Bernard.)

8. *Great Belt Strait Crossing* (*1998*) — The Storebælt suspension bridge, located in Denmark, has a central span of 1624 m. It is the main piece of a complex comprising a combined highway and railway bridge 6.6 km long, a twin tube tunnel 8 km long, and a 6.8-km-long highway bridge (Figure 64.8). This link is part of one of the most ambitious projects in Europe, to join Sweden and the Danish archipelago to the European Continent by a series of bridges, viaducts, and tunnels, which can accommodate highway and railway traffic.

64.2. Design

64.2.1 Philosophy

To allow for the single internal market setup, the European legislation includes two directive types:

1. Directives "products," whose purpose is to unify the national rules in order to remove the obstacles in the way of the free product movement.
2. Directives "public markets," aiming to avoid national or even local behaviors from owners or public buyers.

By experience, the only means of ensuring that a bid based on a calculation method practiced in another state is not dismissed is to have a common set of calculation rules. These rules do not necessarily require the same numerical values.

Consequently, the European Community Commission has undertaken to set up a complex of harmonized technical rules with regard to building and civil engineering design, to propose an alternative to different codes and standards used by the individual member states, and finally to replace them. These technical rules are commonly referred to as "Structural Eurocodes."

The Eurocodes, common rules for structural design and justification, are the result of technical opinion and competence harmonization. These norms have a great commercial significance. The

FIGURE 64.8 Storebælt Bridge. (Courtesy of Cowi Consult.)

Eurocodes preparation began in 1976, and drafts of the four first Eurocodes were proposed during the 1980s. In 1990 the European Economical Community put the European Normalization Committee in charge of developing, publishing, and maintaining the Eurocodes.

In general, the Eurocode refers to an Interpretative Document. This is a very general text which makes a technical statement. In the European Community countries the mechanical resistance and stability verifications are generally based on consideration of limit states and on format of partial safety factors, without excluding the possibility of defining safety levels using other methods, for example, probability theory of reliability.

From this document which heads them up, the Eurocodes deal with projects and work execution modes. Numerical data included are given for well-defined application fields. Therefore, the Eurocodes are not only frameworks that define a philosophy allowing the various countries the possibility to tailor the contents individually, they are something completely unique in the normalization field.

A norm defines tolerances, materials, products, performances. The Eurocodes are entirely different because they attempt to be design norms, i.e., norms that define what is right and what is wrong. That is a unique venture of its kind.

The transformation of the Eurocodes into European norms was begun in 1996 and will be reality in 2001 for the first ones. For about 5 years before their final adoption, both the Eurocodes and the national norms will stay applicable.

Of course, there exists a need for connection between Eurocodes and various national rules. Variable numerical values and the possibility of defining certain specifications differently allow this adaptation. From 2007 to 2008 national norms will be progressively withdrawn. Concerning bridges, from 2008 to 2009 only the Eurocodes will be applicable.

These texts are completely coherent, thus it is possible to go from one to the other with coherent combinations. This coherence expands to the building field where its importance is more significant. Moreover, these texts are merely a part of vast normative whole which refers to construction norms, product norms, and test norms.

The Eurocodes are written by teams constituted of experts from the main European Union countries, who work unselfishly for the benefit of future generations. For this reason they are the fruit of a synthesis of different technical cultures. They constitute an open whole. Texts have been written with a clear distinction between principles of inviolable nature and applications rules. The latter can be modulated within certain limits, so that they do not act as a brake upon innovation, and appear as a decisive progress factor. They allow, by constituting an efficient rule of the game, the establishment of competition on intelligent and indisputable grounds.

The Eurocodes applicable to bridge design are as follows.

Eurocode 1:	Basis of design and actions on structures [1]
Part 2	Loads: dead loads, water, snow, temperature, wind, fire, etc
Part 3	Traffic loads on bridges
Eurocode 2:	Concrete structure design [2]
Part 2:	Concrete bridges
Eurocode 3:	Steel structure design [3]
Eurocode 4:	Steel–concrete composite structure design and dimensioning [4]
Eurocode 5:	Wooden work design [5]
Eurocode 6:	Masonry structure design [6]
Eurocode 7:	Geotechnical design [7]
Eurocode 8:	Earthquake-resistant structure design [8]
Eurocode 9:	Aluminum alloy structure design [9]

64.2.2 Loads

The philosophy of Eurocode 1 is to realize a partial unification of concepts used to determine the representative values of the actions. In this way, most of the natural actions are based on a return period of 50 years. These actions are generally multiplied by a ULS (ultimate limit state) factor taken as 1.5. The return period depends on the reference duration of the action and the probability of exceeding it. This return period is generally 50 years for buildings and 100 years for bridges. This definition is rather conventional. At the moment, the Eurocode is a temporary norm. Consequently, the Eurocode 1 annex make it possible to use a formula which allows one to change the return period. With regard to traffic loads, Eurocodes constitute a completely new code, not inspired by another code. That means the elaboration was done as scientifically as possible.

The database of traffic loads consists of real traffic recordings. The highway section chosen is representative of European traffic in terms of vehicle distribution. On these real data, a certain number of mathematical processes are realized. But not all data were processed by mathematics and probability. Some situations allow definition of the characteristic load. These are obstruction situations, hold-up situations on one lane with a heavy but freely flowing traffic on the other lane, and so forth, i.e., realistic situations.

All these elements were mathematically extrapolated so that they correspond to a 1000-year return period, that is to say, a 10% probability of exceeding a certain level in 100 years. The axle distribution curve leads one to take into account a 1.35 ULS factor instead of 1.5 for a heavy axle. Concerning abnormal vehicles, the Eurocode gives a catalog from which the client chooses. The Eurocode defines as well, how an abnormal vehicle can use the bridge while traffic is kept on other lanes, which is rather realistic.

With regard to loads on railway bridges, the UIC models were revised in the Eurocode. Loads corresponding to a high-speed passenger train were also introduced in the Eurocode.

There are no military loads in Eurocodes. This type of loads is the client responsibility.

Concerning the wind, the speed measured at 10 m above the ground averaged over 10 min, with a 50-year return period, is taken into account. This return period seems to be somewhat conventional, because this speed is transformed into pressure by models and factors themselves including safety margin.

FIGURE 64.9 Oise Bridge. (Courtesy of Fred Boucher, SANEF.)

The most detailed studies show that the return period of the characteristic wind pressure value is rather contained by the interval between 100 and 200 years. After multiplication by the 1.5 ULS factor, this characteristic value has a return period indeed contained by the interval between 1000 and 10,000 years. The code also defines a dynamic amplification coefficient, which depends on the geometric characteristics of the element, its vibration period, and its structural and aerodynamic damping.

With regard to snow loads, the Eurocodes give maps for each European country. These maps show the characteristic depth of snow on the ground corresponding to a 50-year return period. Then this snow depth is transformed into snow weight taking into account additional details.

It is the same case for temperature. The characteristic value is the temperature corresponding to a 50-year return period. The characteristic value for earthquake loads, in Eurocode 8, corresponds as well to a 10% probability of exceeding the load in 50 years.

Therefore, the philosophy is rather clear with regard to loads. Some people wish to go toward greater unification, but it seems to be difficult to realize. Nevertheless, the load definition constitutes a comprehensible and homogeneous whole which is finally satisfactory.

64.3 Short- and Medium-Span Bridges

64.3.1. Steel and Composite Bridges

64.3.1.1 Oise River Bridge

In France, the Paris Boulogne highway link crosses the River Oise on a single steel concrete composite bridge (Figure 64.9). The bridge is 219 m long with a 105-m-long main span over the river and two symmetric side spans. The foundation of the bridge consists of 14 2.80-m-long, about 30-m-deep, diaphragm walls with variable thickness. Pier and abutment design is standard.

FIGURE 64.10 Roize Bridge. (Courtesy of Jean Muller International.)

The bridge deck is a composite structure, 2.50 m deep at midspan and on abutments, and 4.50 m deep on the piers. The steel main girders are spaced 11.40 m. The main girder bottom and top flange widths are constant, but their thicknesses vary continuously from 40 to 140 mm. The concrete slab has an effective width of 18 m. It is transversely prestressed with 4T15 cables, six units every 2.50 m.

The deck steel structure was assembled in halves, one behind each abutment on the embankment. Each half was launched over the river and welded together at midspan. The concrete deck slab was poured using two traveling formworks. The midspan area was poured first, followed by the pier areas.

Since 1994, the link has carried two traffic lanes, which will continue until the foreseen construction of a second parallel bridge.

64.3.1.2 Roize River Bridge

The Roize Bridge carries one of the French highway A49 link roads. Its deck was designed by Jean Muller (Figure 64.10). The choice made was a result of 10 years of studies on reducing the weight of medium-span bridge decks. Here the weight saving was obtained by replacing prestressed concrete cores by steel trusses constituting two triangulation planes (Warren-type) inclined and intersecting at the centerline of the bottom flange, by using a bottom flange formed of a welded-up hexagonal steel tube, and by reducing the thickness of the top slab by the use of high-strength concrete prestressed by bonded strands. The bridge was completed in 1990.

Indeed, innovation of this structure lies in its modular design. The steel structure is composed of tetrahedrons built in the factory, brought to site, and then assembled. The concrete slab also consists of prefabricated elements assembled *in situ.*

The deck is prestressed longitudinally by external tendons to keep a normal compression force in the upper slab on the piers, and to reduce the steel area of the bottom. It is also prestressed transversely.

FIGURE 64.11 Saint Pierre Bridge. (Courtesy of Albert Berenguier, Egis Group.)

The Roize Bridge structure has several advantages: light weight, low consumption of structural steel, industrialized fabrication, ease and speed of assembly, adaptability to complex geometric profile, durability. The basic characteristics are length = 112 m; width = 12.20 m; equivalent thickness of B80 concrete = 0.18 m; structural steel = 112 kg/m^2 of deck; pretensioned prestress = 17 kg/m^3; transverse prestress = 15 kg/m^3; longitudinal prestress = 32 kg/m^3.

64.3.1.3 Saint Pierre Bridge

This bridge is located in the historical center of Toulouse in the southwest of France. Its architecture is inspired by 19th century metal truss bridges with variable depth, while using modern technologies for the execution (Figure 64.11). The bridge is a 240 m long steel–concrete composite structure, partially prestressed. The span lengths are the following: 36.88 m, 3 × 55.00 m, 36.88 m.

It is founded on 1.80-m-diameter molded piles. Each pair of piles is linked by a reinforced concrete box girder. This structure supports a pier consisting of two elements. The deck rests on inclined elastomeric bearings so that the bridge works as a frame in longitudinal direction.

The longitudinal composite structure is made up of two lateral metal truss girders. These girders of variable depth are spaced 11.4 m apart with a cross-beam joining them every 14 m. Both main girders and cross-beams are connected to the concrete slab. The concrete slab is 25 cm thick on the central part bearing the traffic lanes. Toward the edges the slab is 27 cm thick and is placed 75 cm higher than the central part, accommodating the sidewalks.

The structure is prestressed longitudinally by 4K15 cables constituted by greased strands located toward the edges of the slab. Transversely, it is prestressed by greased monostrands located in the slab central part. The steel deck structure is erected from the piers supporting on temporary piling. The concrete slab is poured *in situ* with formwork supported by the now self-supporting steel structure.

This bridge is perfectly integrated into its environment of historic monuments, and opened to traffic in 1987.

FIGURE 64.12 A1 highway overpasses. (Courtesy of J. P. Houdry, Egis Group.)

64.3.2. Concrete Bridges

64.3.2.1 Channel Bridges: Overpasses over Highway A1

A new segmental design for overpasses was developed in France in 1992 to 1993, taking into account the necessity of standardization. The bridges have decks comprising a single transverse slab supported by two longitudinal lateral ribs (Figure 64.12).

This concept, suitable for a wide variety of bridge types with span lengths of between 15 and 35 m, is encompassed in the following ideas:

- The deck is built using precast segments, match-cast, and longitudinally prestressed.
- The segments are transversely prestressed using greased monostrands.
- The lateral ribs are used as barriers.

The main advantages of this type of concept are the possibility of building the overpass without disruption of traffic very quickly, with longer spans, thus fewer spans (two instead of four spans), than for the usual precast conventional overpasses.

64.3.2.2 Progressively Placed Segmental Bridges

Fontenoy Bridge

Fontenoy Bridge is 621 m long and open to traffic in 1979. It allows the crossing of the River Moselle in the north east of France with the following spans: 43.12 m, 10 × 52.70 m, 50.80 m. The foundations are either coarse aggregate concrete footings or bored piles, depending on the resisting substratum. On typical piers the bearings are of the elastomeric type, and on the abutments they are of the sliding type. The deck is a simply supported concrete box girder, 10.50 m wide, with two inclined webs and a constant depth of 2.75 m.

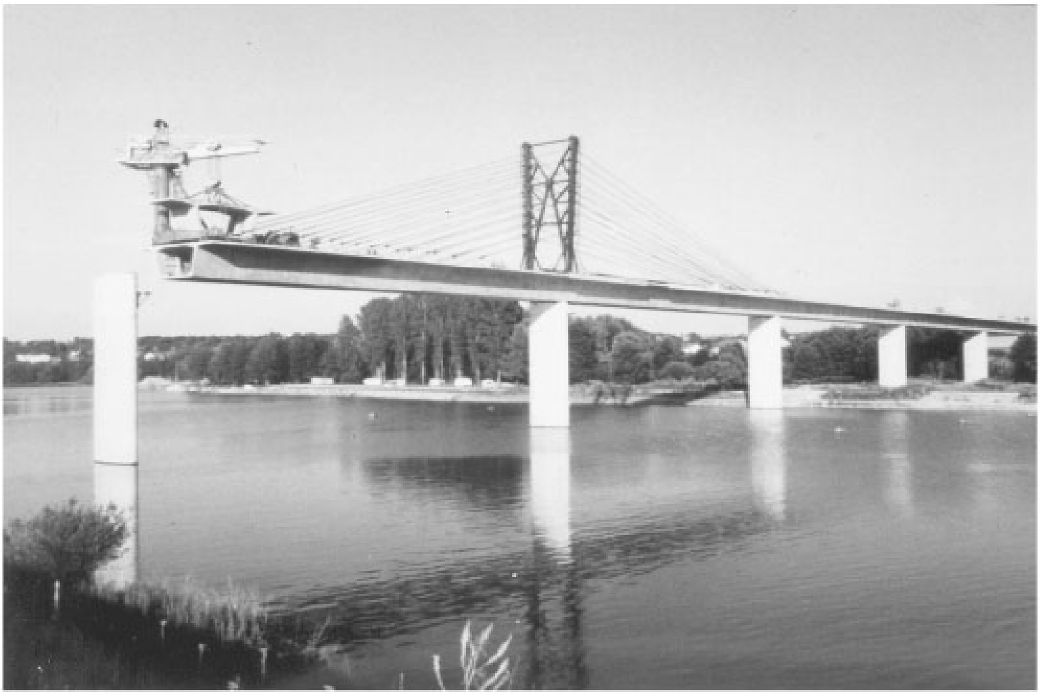

FIGURE 64.13 Fontenoy Bridge. (Courtesy of Campenon Bernard.)

The progressive placement method is used to build the deck, starting at one end of the structure, proceeding continuously to the other end (Figure 64.13). A movable temporary stay arrangement is used to limit the cantilever stresses during construction. The temporary tower is located over the preceding pier. All stays are continuous through the tower and anchored in the previously completed deck structure.

Precast segments are transported over the completed portion of the deck to the tip of the cantilever span under construction, where they are positioned by a swivel crane that proceeds from one segment to the next. The box girder is longitudinally prestressed by internal 12T13 units.

Les Neyrolles Bridge

Nantua and Neyrolles Viaducts allow the A40 highway to link Geneva, Switzerland, to Macon, France. The Neyrolles Viaducts have a total length of 985.5 m divided into three independent structures. It is composed of 20 spans of 51 m approximately, except for one span of 62 m which crosses the "Bief du Mont" stream (Figure 64.14). The deck is a concrete box girder approximately 11 m wide. The box girder was erected of precast match-cast segments.

The assembly was performed by asymmetric cantilevering by means of temporary stays and a deck-mounted swivel crane. The mast ensured the stability through the back stays carried by the previous span. The mast allowed erection of spans up to 60 m. The side spans at the abutments could not be assembled likewise because of the absence of a balancing span. Consequently, these span segments were placed on falsework and finally each span was prestressed and put on its definitive supports by means of jacks. The largest span (62 m) was assembled by both methods of construction mentioned.

The first phase consisted of assembly by stay-supported asymmetric cantilevering until the last stay available. The second phase consisted in erecting the last precast segments on falsework. The bridge was completed in 1995.

FIGURE 64.14 The second Neyrolles viaduct. (Courtesy of Campenon Bernard.)

64.3.2.3 Rotationally Constructed Bridges

Gilly Bridge

The Gilly Bridge, close to Albertville in France, consisting of two perpendicular decks was opened to traffic in 1991. The main bridge crosses the river Isère and the access road to the Olympic site resorts (Figure 64.15).

It is a prestressed concrete cable-stayed bridge, with two spans, 102 m long above the river and 60 m long above the road. The A-shaped pylon is tilted backward 20°. The other bridge supports are a standard abutment on the left bank and a massive abutment acting as counterweight on the right bank. Transversely, the 12-m concrete deck consists of two 1.90-m-deep and 1.10-m-wide lateral ribs with cross-beams spaced 3.0 m supporting the top slab.

The A-shaped pylon was built vertically. It was tilted to its definite position by pivoting around two temporary hinges located at its basis, the pylon being held back by two 19T15 cables. After tilting, hinges were frozen by prestressing and concreting.

FIGURE 64.15 The Gilly Bridge. (Courtesy of Razel.)

The 162-m-long main bridge deck was concreted on a general formwork located on the right bank, parallel to the river. After concreting and cable-stay tensioning, the deck was placed in its definite position by a 90° rotation around a vertical axis. During the deck rotation the whole structure weighing 6000 t is supported on three points. Vertical reactions are measured continuously by electronic equipment to check dynamic effects.

Resorting to original construction methods has allowed realization of a bridge of high quality both structurally and aesthetically.

Ben Ahin Bridge

The Ben Ahin Bridge crossing the river Meuse in Belgium is a cable-stayed asymmetric bridge, 341 m in overall length (Figure 64.16), constructed in 1988. The reinforced concrete bridge deck, partially prestressed, is suspended by 40 cables anchored to a single tower structure. The central span is 168 m long. The deck girder has a box section, 21.80 m wide at the top fiber and 8.70 m at the bottom fiber. The depth, constant along the whole bridge, is 2.90 m.

The entire structure consisting of the tower structure, the stay cables, and the deck girder was constructed on the left bank of the river. After completion it was rotated by 70° relative to the tower axis, in order to swing the bridge around to its final definite position (Figure 64.17). Two pairs of jacks, each 500 ton force, located underneath the pylon sliding on Teflon, and four jacks each 300 ton force, located 45 m from the pylon underneath a stability metal frame, allowed the rotation of the 16,000 ton structure.

This method, already used in France for lighter bridges, was in this case designed to set a world record.

64.3.3. Truss Bridges

64.3.3.1 Sylans Bridge

The Sylans Viaduct runs through the French Jura Mountain complex. In this location, along the shores of a lake, difficulty lies in the uncertainty of the foundation soil since the route runs along a very steep slope whose 30-m-thick surface stratum comprises an eroded and fractured material of very doubtful stability.

FIGURE 64.16 Ben Ahin Bridge. (Courtesy of Daylight for Greisch.)

FIGURE 64.17 Ben Ahin Bridge during rotation. (Courtesy of Photo Studio 9 for Greisch.)

FIGURE 64.18 Sylans Bridge — two parallel decks. (Courtesy of Bouygues.)

The 1266-m-long viaduct comprises 21 60-m-long spans, each composed of two identical parallel decks 15 m apart and staggered 10 m in height (Figure 64.18), and was constructed in 1988. The deck is a prestressed concrete space truss structure 10.75 m wide and 4.17 m deep all along the bridge. It consists of 586 precast segments, i.e., 14 segments for each viaduct span.

Each typical concrete segment consists of two slabs linked by four inclined planes of diagonal prestressed concrete braces of 20 cm^2 cross section, assembled in pairs in the form of Xs. For every segment the diagonal braces are precast separately with a concrete of 65 MPa cylinder strength, and assembled with the segment-reinforcing cage. Then, the top and bottom slabs are poured with 50-MPa concrete. Finally, the diagonals are prestressed.

The deck segments are put in place by the cantilever method using a 135 m long launching girder. The deck prestressing consists of four families:

- Cantilever cables located below the top slab: 4T15 units;
- Strongly inclined cables from pier to withstand the shear force: 12T15 units;
- Horizontal continuity cables on and inside the bottom slab: 12T15 units;
- Horizontal cables in the top and the bottom slabs: respectively, 4T15 and 7T15 units.

The deck bears on its piers through reinforced elastomeric bearings.

Piers are supported by 6- to 35-m-tall, 4-m-diameter caissons. A circular concrete cap is cast on the caissons and anchored to the hard bedrock. In all, 3.5 years were necessary to build this bridge designed with the intent of achieving the maximum lightness possible.

64.3.3.2 Boulonnais Bridges

The three Boulonnais Viaducts are located on A16 highway which links Great Britain to the urban area of Paris, France, via the Channel Tunnel, and was completed in 1998. Their characteristics are as follows:

Name	Length, m	Span Distribution	Height above the Valley Floor, m
Quéhen	474	44.50 + 5 × 77.00 + 44.50	30
Herquelingue	259	52.50 + 2 × 77.00 + 52.50	25
Echinghen	1300	44.50 + 3 × 77.00 + 93.50	75
		5 × 110.00 + 93.50 + 3 × 77.00 + 44.50	

FIGURE 64.19 Boulonnais Bridges — pier transparency. (Courtesy of Jean Muller International.)

The foundations consist of diaphragm walls to a depth of 42 m. The typical pier is based on four diaphragm walls, whereas tallest piers are founded on eight diaphragm walls. These diaphragm walls were realized using drilling mud. Quantities are 3800 m of diaphragm walls, a third of which was excavated with a cutting bit; 10,000 m^3 of concrete; 870 tons of reinforcing steel.

Each pier consists of two slender shafts, of diamond shape. These are linked on top by an aesthetically pleasing pier cap, on which the deck is supported (Figure 64.19).

The gap between the two pier shafts increases the bridge transparency created by the truss at deck level. The four tallest pier shafts are linked on their lower part by a transverse wall to increase the buckling stability.

The deck is a composite structure made of match-cast segments, assembled by cantilever method. The three bridges are formed by 524 segments. The deck structure consists of two prestressed concrete slabs, joined by four inclined V-shaped steel planes. Six inclined planes improve the transverse behavior of the deck near bridge supports.

The 23-cm-thick top slab is stiffened by four 70-cm-deep longitudinal ribs located in the diagonal planes. The top slab is prestressed transversely. The 27-cm-thick bottom slab is stiffened by longitudinal ribs and by two transverse beams per segment.

The deck is built by the cantilever method using a 132-m-long launching gantry weighing 500 tons. Segments, weighing 125 tons at the minimum, are put in place symmetrically in pairs. Imbalance between both cantilevers during erection never exceeds 20 tons.

FIGURE 64.20 Dole Bridge. (Courtesy of Campenon Bernard.)

The Echinghen Viaduct is located on a very windy site, a few kilometers from the Channel shore. Gusts of wind exceed 57 km/h 103 days a year, and 100 km/h 3 days a year. A project-specific calculation taking into account the turbulent wind was developed to study the bridge construction phases. This calculation led to imposition of very rigorous cantilever construction kinematics.

Moreover, a wind screen was designed for the windward side of the deck in prevailing wind to avoid very strict traffic limitations.

64.4. Long-Span Bridges

64.4.1 Girder Bridges

64.4.1.1 Dole Bridge

The Dole Bridge, completed in 1995, crossing the River Doubs in France, is 496 m long. It is a continuous seven-span box girder with variable depth. The typical span is 80 m long (Figure 64.20). The deck is erected by the balanced cantilever method using a traveling formwork.

The deck is a composite structure, 14.5 m wide, with two concrete slabs and two corrugated steel webs. The webs are welded to connection plates fixed to the top and bottom slabs by connection angles. Pier and abutment segments are strictly concrete segments.

The deck is longitudinally prestressed by three tendon families:

- Cantilever tendons, anchored on the top slab fillets: 12T15 tendons;
- Continuity tendons, located in the bottom slab in the central area of each span: 12T15 tendons;
- External prestressing, tensioned after completion of the deck, with a trapezoidal layout. The technology used allows removal and replacement of any tendon.

The Dole Bridge is the fourth bridge with corrugated steel webs erected in France.

FIGURE 64.21 Nantua Viaduct. (Courtesy of Campenon Bernard.)

64.4.1.2 Nantua Bridge

Nantua and Neyrolles Viaducts allow the A40 highway to link Geneva, Switzerland, to Macon, France. The Nantua viaduct is 1003 m long, divided in 10 spans. It was constructed in 1986. Its height above the ground varies from 10 to 86 m (Figure 64.21).

The western viaduct extremity is a 124-m-long span supported in a tunnel bored through the cliff. To balance this span, a concrete counterweight had to be constructed inside the cliff in a tunnel extension. The counterweight translates on sliding bearings of unusual size. The relatively large spans (approximately 100 m long) necessitated a variable-depth concrete box girder.

The construction principle for the deck is segments cast *in situ* symmetrically on mobile equipment. The 11.65-m-wide deck, for the first two-way roadway section of the highway, is longitudinally prestressed by cables located inside the concrete.

Various foundation methods were used, necessitated by differences in the soil bearing capacity.

64.4.2 Arch Bridges

64.4.2.1 Kirk Bridges

These concrete arch bridges were designed to provide a link between the Continent and the Isle of Kirk (former Yugoslavia). The two arches have spans of 244 and 390 m, respectively (Figure 64.22). The largest span represents a world record in its category. The box-girder arches are 8 m (width) × 4 m (height) and 13 m (width) × 6.50 (height), respectively.

The construction was carried out in two phases: In the first phase a box-girder arch, constituting the central part of the bridge, was made by using onshore precast segments. The assembly was performed by cantilevering from both banks by means of a mobile gantry (which was carried by the part of the arch already constructed) and of temporary stays. The use of precasting provided a better quality of concrete, a more precise tolerance of fabrication and reduced construction time. The keystone of the arch was likewise placed by means of a mobile gantry. The closure of the two

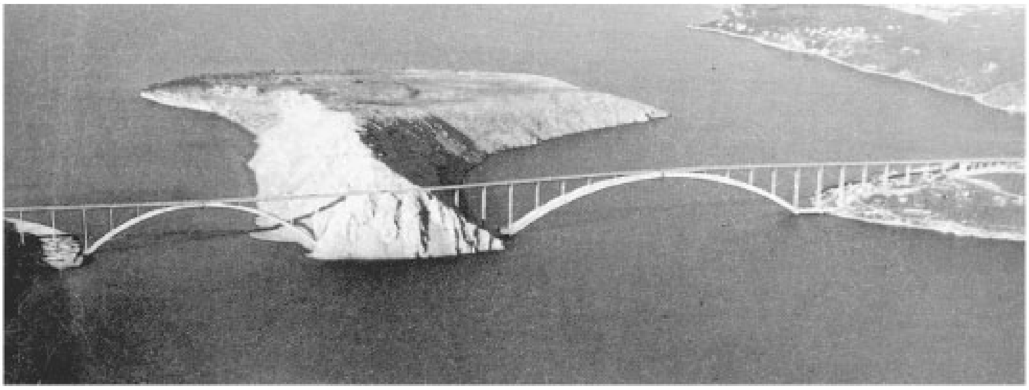

FIGURE 64.22 Kirk Bridges. (*Source*: Leonhardt, F., Ponts/Puentes — 1986 Presses Polytechniques Romandes. With permission.)

FIGURE 64.23 La Roche Bernard Bridge. (Courtesy of Campenon Bernard.)

semiarches was controlled by means of hydraulic jacks. The second phase of construction consisted of placing the lateral parts of the bridge, composed of large beams connected to the central arches. An *in situ* concreting of the joints between the precast segments and vertical and transversal prestressing ensure the monolithic integrity of the structure.

64.4.2.2 La Roche Bernard Bridge

La Roche Bernard Bridge, completed in 1996, is 376 m long and 20.80 m wide. It crosses the River Vilaine in Brittany, France, by an arch spanning 201 m and small approach spans (Figure 64.23).

The deck is a composite structure consisting of a steel box girder, 1.67 m deep with a trapezoidal shape, covered by a thin 23-cm-thick prestressed concrete slab. It is supported on four piers founded on the ground and six small piers fixed on the arch. The piers are spaced between 32 and 36 m. Like many other composite decks, the box girder is launched using a launching nose (20 m long); the slab is cast afterward. The concrete arch is 8 m wide with a height varying from 3.50 m at the springing to 2.90 m at the crown.

For the erection, the balanced cantilever process was applied using traveling formwork. Moreover, three temporary bents with 500 t jacks and two temporary pylons were successively used. The temporary bents were located below the segments S3 (the third), S5, or S15, and the temporary pylons were located on the riverbank or on the top of segment S15.

Except for segments S0 (springing segment) to S6 using the temporary, all other segments were erected by use of temporary pylons and temporary stays (11T15 and 13T15 units). The segments S7 to S13 were erected by means of stays fixed to the pylon on the riverbank and the temporary bent below S5.

The other segments S17 to 27 were erected by the use of stays fixed on the main pylon and by the use of bents below segments S5 and S15. The main pylon was placed on segment S15 and anchored in the previously erected segments.

While the number of stays fixed on the main pylon increased during erection, the number of stays on the other pylon decreased. Consequently, when the segment S20 was supported by the temporary stays, fixed to the main pylon, all stays on the other pylon had been removed.

64.4.2.3 Millau Bridge

To allow the highway A75, in France, to link two plateaus separated by the Tarn Valley five different crossings were designed. One of the proposals for traversing the 300-m-deep and 2500-m-wide valley was developed by JMI and consisted on a large arch and two approach viaducts. Two types of structures were designed for the deck: the basic scheme was based on a concrete box girder, while the alternative project was based on a steel–concrete composite box girder. Many features are common for the two designs, which is the reason only the basic project is described below:

The crossing is divided into three viaducts:

- The north approach viaduct: 486.50 m long, with four spans of between 66.50 and 168 m;
- The main viaduct: one arch spanning the 602 m over the river (Figure 64.24);
- The south approach viaduct: 1445.5 m long, with eight spans of 168 m and one shorter span of 101.50 m.

The 24 m wide roadway is carried by a 8-m-wide concrete box girder whose depth varies from 4 m at midspan to 10 m on pier, except at the central part of the arch where the depth is constant and equal to 4 m. Transversely, both 8-m-wide cantilevers are supported by struts, spaced 3.50 m. The box-girder webs are vertical and 500 mm thick. The bottom slab thickness decreases from 600 mm on pier to 300 mm at midspan.

For the approach viaducts and the first spans on the arch, the balanced cantilever method using traveling formwork is applied. Two families of PT are used: internal PT split in cantilever or continuity units and external PT for general continuity units.

Due to the great length of this bridge, an expansion joint is placed at midspan between P12 and P13, about 1500 m from the north abutment. This joint is equipped with two longitudinal steel girders simply supported on either side of the joint, which allow partial transfer of the bending moment and transfer of the shear force while reducing the deflections.

64.4.3. Truss Bridges

Bras de la Plaine Bridge

The future bridge, located on Isle of La Réunion, in the Indian Ocean (France), will span over the Bras de la Plaine valley which has highly inclined slopes (80°) and reaches a depth of 110 m.

The single-span prestressed composite truss deck, 270 m long, has an innovative static scheme: two cantilevers are restrained in counterweight abutments and linked at midspan by a hinge

FIGURE 64.24 Millau Bridge. (J. P. Houdry, Courtesy of Alain Spielmann.)

FIGURE 64.25 Bras de la Plaine Bridge. (Courtesy of Jean Muller International.)

(Figure 64.25). The deck structure, 17 m deep near the abutments and 4 m deep at midspan, comprises two concrete slabs linked by two inclined truss planes.

The upper 60 MPa (cylinder) concrete slab is 12 m wide. The lower 60 MPa (cylinder) concrete slab has a parabolic profile with variable thickness and width. Each truss panel consists of circular steel diagonals connected directly to the concrete slabs.

FIGURE 64.26 Theodor Heuss Bridge. (*Source*: Beyer, E., Bruckenbau, Beton Verlag, 1971. With permission.)

At midspan, four girders allow transmission of vertical and horizontal shear force and horizontal bending moment. The prestressing system is composed of internal tendons only located in the upper slab. Deck erection will begin by the end of 1999 using the standard cantilever erection method.

64.4.4. Cable-Stayed Bridges

64.4.4.1 Theodor-Heuss bridge

This bridge, also called "Northbridge", belongs to a family of three steel structures on the Rhine River in Düsseldorf, Germany. Northbridge is the first of the two, built in 1957, and belongs to the first generation of cable-stayed bridges.

This type of bridge was conceived to allow the crossing of large spans without intermediate ground support using cables to support the deck elastically in construction (Figure 64.26). The steel deck is 26.60 m wide and 476 m long divided into two approach spans of 108 m and the main span of 260 m. On the flooded riverbank, a five-span approach bridge extends the cable-stayed bridge. The four pylons are 41 m high, slender (1.90 long vs. 1.55 m wide) and spaced 17.60 m.

The main span is supported by four pairs of three cables fixed to the pylons. The three cables are parallel, set out like a harp in a single vertical plane and anchored in each edge of the deck with a spacing 36 m. Due to this spacing, the deck must be stiff, hence a depth of 3.14 m. This depth is extended further on to the approach bridge.

Regarding its erection, it was one of the first times that the balanced cantilever method was applied. The first cantilever segment of 36 m long was erected with the deck elastically supported with one pair of stays. The second segment and the others were erected at midspan.

64.4.4.2 Saint Nazaire Bridge

The bridge of St. Nazaire near the mouth of the Loire River in France, is approximately 3350 m long (Figure 64.27). It is composed of a central part, a 720-m cable-stayed steel bridge, and of two approach viaducts consisting, respectively, of 22 and 30 spans made up of precast concrete girders, each span being 50 m long.

The cable-stayed bridge has a central span 404 m long and two 158 m lateral spans. It is composed of steel box girders, 15 m wide. The construction of the cable stayed bridge, completed in 1975, was carried out in three phases.

FIGURE 64.27 Saint Nazaire Bridge. (Courtesy of Jean Muller International.)

1. The first phase consisted of the construction of the side spans. The steel box girders were assembled in the factory to pieces of 96 m. Then two segments each 96 m were assembled on site by welded joints and transported by two barges to be ultimately hoisted up to their final position.
2. In the second phase, the segments constituting the pylons were assembled on the bridge deck. Then the pylon was lifted by rotation to reach its definitive position.
3. The third phase consisted in erecting the central span as two cantilevers of 197.20 m of length with closure joint at midspan. The segments were lifted from barges with beam-and-winch system.

64.4.4.3 Brotonne Bridge

The Brotonne Bridge was designed to cross the River Seine downstream from Rouen, France (Figure 64.28). It was opened to traffic in 1977. It is composed of two approach viaducts and a cable-stayed structure with a 320-m-long central span. The deck consists of a prestressed concrete box girder 3.97 m deep and 19.20 m wide (Figure 64.29). The stays and the pylon (Figure 64.30) are placed in a single plane along the longitudinal axis of the bridge. The approaches and the main bridge were erected in the same way. In both cases a cantilever construction was used with success. The length of the segments was 3 m.

The segments were cast in place except for the webs which were precast and prestressed. The erection of the deck-girder consisted of extending the bottom slab form of the traveling formwork carried by the previous completed segment, then placing the precast webs that formed the basic shape and acted as a guide for the remaining traveling formwork. The webs were transported and lifted by a tower crane. Concerning the main bridge, the stays were tensioned in every two segments and were anchored in the top slab axis. For the segments, two inclined internal stiffeners were provided to transfer vertical loading generated by the stays. These stiffeners were prestressed.

FIGURE 64.28 Brotonne Bridge. (Courtesy of Campenon Bernard.)

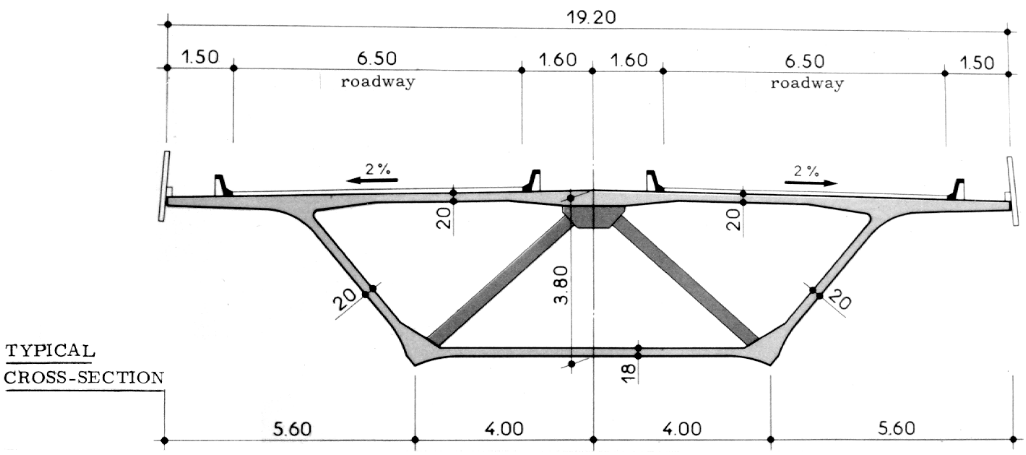

FIGURE 64.29 Brotonne Bridge — typical cross section. (Courtesy of Campenon Bernard.)

64.4.4.4 Normandie Bridge

Since 1994, the Normandie Bridge has allowed the A29 highway to pass over the River Seine near its mouth in northern France (see Figure 64.7). It is a cable-stayed bridge, 2141 m long with the following spans:

$$27.75 \text{ m} + 32.50 \text{ m} + 9 \times 43.50 \text{ m} + 96.0 \text{ m} + 856 \text{ m}$$
$$\text{(longest cable stayed span in the world)} + 96.00 \text{ m} + 14 \times 43.50 \text{ m} + 32.50 \text{ m}$$

FIGURE 64.30 Brotonne Bridge — pylon base reinforcement. (Courtesy of Campenon Bernard.)

The central span is made of three parts: 116 m of prestressed concrete section, 624 m of steel section, and 116 m of prestressed concrete section.

The deck cross section is designed to reduce wind force on the bridge and to give a high torsional rigidity. At the same time its shape is adapted for both steel and concrete construction. It is 22.30 m wide and 3.0 m deep. The concrete deck is a three-cell box girder with two vertical webs and two inclined lateral webs. The steel deck is an orthotropic box girder constituted by an external envelope, stiffened by diaphragms and by trapezoidal stringers.

The A-shaped concrete pylon is extended by a vertical part where stays are anchored (Figure 64.31).

Three different construction methods were used for the Normandie Bridge erection:

1. The approach spans (southern approach 460 m, northern approach 650 m) were put in place by the incremental launching method from the embankment, using a launching nose.
2. On both sides of the 200-m-tall pylons, the superstructure was built by the cable-stayed balanced cantilever method with segments cast *in situ* in a traveling formwork. From the 90-m-long cantilevers, the 96-m side span was joined to the incrementally launched spans. Then the construction of the concrete deck was finalized with an additional 20 m of cast *in situ* cable-stayed cantilever on the river side.
3. The central part of the main span was erected by 19.65-m-long steel segments supplied by barge, lifted up by crane, and finally welded to the previous segment. A pair of cables was tensioned before moving the crane to lift the following segment.

The bridge foundations are the following:

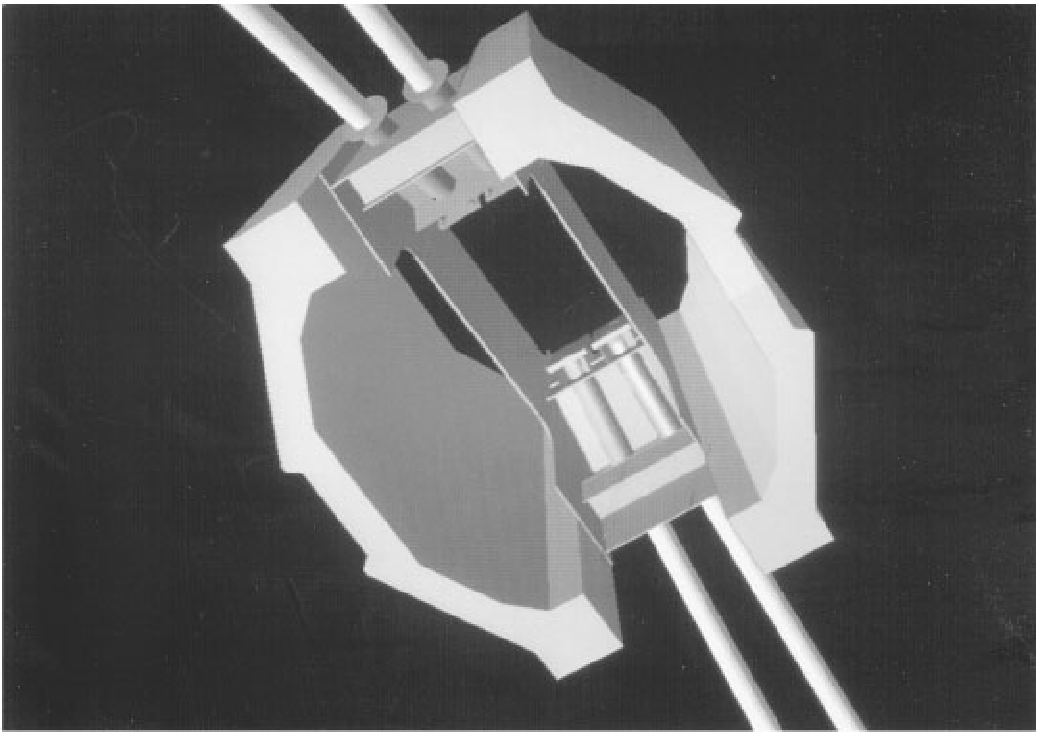

FIGURE 64.31 Normandie Bridge — cable stay anchorages. (Courtesy of Campenon BErnard.)

- Piers and abutments are founded on 1.50-m-diameter, 40-m-deep bored piles — four or five piles per pier.
- The towers are founded on 2.10-m-diameter, 50-m-deep bored piles — 14 piles for each pylon leg.

64.4.4.5 Bi-Stayed Bridge

The clear span of a conventional cable-stayed bridge is limited by the capacity of the deck to resist the axial compressive loads near the pylons created by the horizontal component of the stay forces. For the current materials (70 MPa high-strength concrete, for example), the limit span is between 1200 and 1500 m, depending upon the imagination and the boldness of the designer. Beyond this limit, only suspension bridges allow spanning very large crossings. This situation has now changed, thanks to the new so-called bi-stayed concept.

Deck construction still proceeds in the same fashion as for conventional cable-stayed bridges; starting from the pylons outwardly in a symmetrical sequence, the deck is suspended by successive stays. At a certain stage of construction [for a deck length equal to "a_1," Figure 64.32: (13a)] on either side of each pylon, for example), the deck axial load will have absorbed the full capacity of the materials (with provision for the future effect of live loads). No additional deck length may be added, without exceeding the allowable stresses.

At this stage, a second family of stays is installed [(Figure 64.32 (13b)], assigned to suspend the center portion of the main span. These additional stays are symmetrical with one another with regard to the main span centerline and no more with regard to the pylon. Furthermore, they are no longer anchored in the deck itself, but rather in outside earth abutments at both ends of the bridge, much in the same way as the main cables of a suspension bridge. The vertical load assigned to each stay is now balanced along a continuous tension chain, made up of the center portion of

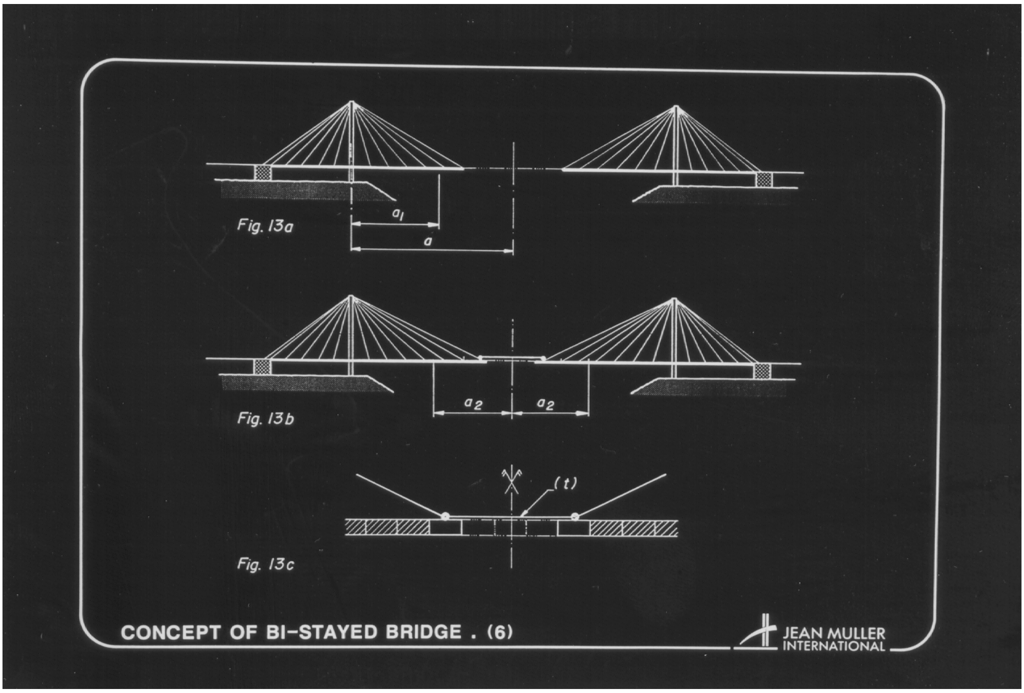

FIGURE 64.32 Bi-stayed bridge. (Courtesy of Jean Muller International.)

the deck (subjected to tension loads), associated with two symmetrical stays, deviated above the pylon heads, to be finally anchored outside the bridge deck.

Along the deck, an axial compression load appears in the vicinity of the pylons (created by the first family of stays), changed into a tension axial load at the centerline of the main span (created by the second family of stays).

In this first application of the new concept, one may increase the maximum clear span in the ratio ($a_1 + a_2/a_1$), i.e., about 1.5.

In fact, it is possible to go much beyond that stage, while improving the quality of the structure, by using prestressing [Figure 64.32 (13c)]. On the deck length suspended by the second family of stays, prestressing tendons are installed to offset at least all axial tension forces due to dead and live loads. When no live load is applied, the deck is subjected to a compression load, which vanishes when the bridge is fully loaded.

With the usual proportions of dead to live loads, it is easily demonstrated that the maximum span length can be multiplied by 2.5. One can now consider with confidence the construction of a clear span of 3000 m.

A practical example of the new concept was prepared for an exceptional crossing in Southeast Asia with a 1 200 m clear main span. The deck carried six lanes of highway traffic, two train tracks, and two special lanes for emergency vehicles. The bridge was also subject to typhoons.

64.5. Large Projects

64.5.1. Second Severn Bridge

The second Severn Bridge provides a faster link between England and Wales. The structure, 5126 m long (Figure 64.33), consists of three parts: the eastern viaduct, 2103 m long; the main cable-stayed bridge, 946.6 m long; and the western viaduct, 2077 m long. From east to west the bridge span lengths are:

FIGURE 64.33 Second Severn Bridge at twilight time. (Courtesy of G.T.M.)

32 m, 58 m, 23 × 98.12 m, 456 m, 23 × 98.12 m, 65 m

1. The approach viaducts are founded on multicellular reinforced concrete caissons, one per pier, precast on land, with a weight varying from 1100 to 2000 according to the piers. These caissons are transported by barge from the precasting yard to the relevant site. The barge is equipped with a pair of crawler tractors of 1500-ton loading capacity.

Of the 47 concrete piers, 38 are precast, representing 338 concrete elements. Three to seven elements joined by wax-grouted vertical prestressing are necessary to build one pier. Two rectangular pier shafts are erected on each foundation caisson.

The approach viaduct deck consists of two parallel monocellular prestressed concrete box girders connected by the upper slab to provide a 33.20-m-wide platform on most of the bridge length. The deck depth varies from 7.0 m on pier to 3.95 m in the span central part.

The approach viaduct deck is divided into about 500-m-long sections. Expansion joints are located at midspan. The typical deck section consists of four spans and two cantilevers supported by five piers.

All spans are made of 3.643-m-long precast segments; these match-cast segments are put in place by the balanced cantilever method with epoxy joints. For this construction a 230-m-long launching gantry weighing 850 tons is used. All prestressing cables are external with all tendons individually protected in wax-grouted HDPE (high density polyethylene) sheaths. Four prestressing cable families can be distinguished:

- Cantilever tendons: 11 to 12 pairs per cantilever
- Continuity bottom tendons: 3 to 4 pairs per span
- Continuity top tendons: 1 to 2 pairs for span
- General continuity tendons: 5 to 6 pairs per span, spread over two spans

2. The bridge environment is particularly constraining: the Severn estuary is subject to the second strongest tides in the world which represents a differential capable of exceeding 14 m, with strong currents of 8 to 10 knots in certain places and occasionally strong winds. Furthermore, 80% of the foundations are exposed at low tide.

This means that the key to this challenge of the tides is a maximum use of prefabricated components. That explains choices made for the approach viaducts: precasting of foundation caissons, piers at sea, deck segments. That explains as well the main bridge pylon cross-beam and the anchorage block precasting, and precasting of the cable-stayed bridge deck elements.

3. The cable-stayed bridge is 946.60 m long. It is a symmetric work with the following span lengths: 49.06 m, 2 × 98.12 m, 456 m, 2 × 98.12 m, 49.08 m. The bridge towers are founded on precast multicellular caissons. Each 137-m-tall tower consists of two rectangular hollow concrete shafts: reinforced concrete for the typical section and prestressed concrete for the stay anchorage area.

Each pylon caisson is equipped with a 45 m^3/h capacity ready-mix plant, and two metallic platforms to store reinforcement and formwork. This equipment allows one to give maximum autonomy to pylon teams. Pylon shafts are concreted *in situ* with a climbing formwork in 3.80-m-long sections. The cross-beams are precast on land and weigh 1300 and 900 tons, respectively. The lower cross-beam is lifted in place by a crane barge and then linked by concreting to the pylon legs. The upper tie beam is lifted and put down on the lower one, and then lifted to its definite position by jacking.

The first cross-beam is located at a 40-m height above the highest tide, the other forming a frame on the level of the stay-cable anchorage area. The main bridge deck is simply supported on the lower pylon cross-beams with transverse stops. It is supported on four secondary piers on both side spans with antiuplift bearings, and last simply supported on the access viaduct extremities.

The deck is a composite structure consisting of

- Two 2.50-m-deep I girders linked every 3.65 m by a truss beam. The distance between the two main girders is 25.2 m.
- A reinforced concrete slab about 35 m wide and 20 cm or 22.5 cm thick for a typical section.

The deck is assembled of 128 precast elements, 34.60 m wide and 7 m long. The steel structure is assembled by bolts at the precasting yard; then the concrete slab is poured except at the connection joint between two consecutive segments. Each standard segment weighing about 170 t is positioned by trailer and transported by barge to the site. The deck segments are lifted and positioned by a pair of mobile cranes located at the end of each cantilever, and bolted to the previous segment. Then two stays are tensioned and the joint with the previous segment is concreted.

The bridge deck is supported by four stay planes, each made up of 60 stays from 19 to 75 T15 strands with a length varying from 35 to 243 m.

4. The second Severn River crossing bridge provides three traffic lanes in each direction, emergency lanes, safety barriers, and lateral wind screens. The construction of this new bridge is financed by private sector. The existing and the new toll bridges are managed by a concessionary group which takes responsibility for design, construction, financing, operating, and maintenance of both bridges.

Over 2 years of study and 4 years of work on site, challenged by the extreme tides, were necessary to build this bridge, located 5 km downstream from the suspension bridge erected in 1966, 30 years earlier.

64.5.2. Great Belt Bridges

The construction of the fixed link across the Great Belt Strait is a bridge and a tunnel project of exceptional dimensions. The Great Belt fixed link consists of three major projects:

FIGURE 64.34 Great Belt Bridges — the railway tunnel. (Courtesy of Jean Muller International.)

1. The railway tunnel under the eastern channel between Zealand and the island of Sprogø, in the middle of the Belt. It is a bored tunnel comprising two single-track tubes each with an internal diameter of 7.7 m and an external diameter of 8.50 m (Figure 64.34). The total tunnel length is 8 km.

Four 220-m-long boring machines have worked down to 75 m below sea level. The twin tunnel tubes are lined with interlocking concrete rings made of precast concrete segments each of a width of 1.65 m in the direction of boring. Each ring consists of six circle segments and a smaller key segment. A total of 62,000 tunnel segments were manufactured.

The twin tunnel tubes are connected at 250-m intervals by cross-passages with an internal diameter of 4.5 m, lined with cast iron segments assembled as rings. Each cross-passage consists of 22 rings of each 18 elements.

The railway tunnel is the second longest underwater bored tunnel, the tunnel beneath the English Channel being the longest.

2. The highway bridge across the eastern channel is 6790 m long. It consists of a suspension bridge with a 1624-m-long main span (see Figure 64.8) and two 535-m-long side spans, and of 23 approach spans totaling 4096 m (14 spans for the eastern approach and 9 spans for the western approach).

The bridge towers are founded on concrete caissons weighing 32,000 tons, placed on the seabed. The two legs of the pylons are cast in climbing formwork from the base to the pylon top 254 m above sea level. Cross-beams interconnect the pylon legs at heights of 125 and 240 m.

The anchor blocks for the suspension cables are also founded on concrete caissons weighing 55,000 tons. The rest of the two anchor blocks, including the special distribution chambers in which the main cables are anchored, are cast *in situ* by a conventional method to the top height of 63.4 m above sea level.

Among the bridge piers, the most part, i.e., 18, are prefabricated. Each pier consists of three elements: a caisson, a lower pier shaft, and finally a top pier shaft. The bridge piers weigh 6000 t

FIGURE 64.35 Great Belt Bridges — 193-m-long approach span. (Courtesy of Cowi Consult.)

on average. Conventional floating cranes are used for assembly of both the caissons and the pier shafts.

The steel superstructure of the main span comprises a fully welded box girder 4 m deep and 31 m wide. After floating the 48-m-long segments to a position under the main cables, they are hoisted into place by winches, and then welded to the previous section.

The two main cables each have diameter of 85 cm and a length of approximately 3 km. Each main cable includes 148 cables, and each cable includes 126 wires with a diameter of 5.13 mm; 20,000 tons of the steel representing a length of 112,000 km constitute the suspension of the bridge.

The steel superstructure of the approach spans comprises a fully welded box girder with a constant girder depth of 6.7 m, a width of 26 m, and a typical span of 193 m (Figure 64.35). The cross section has the same wing shape as the main span girder. The steel girders, each weighing about 2300 tons, are hoisted from a barge by a large floating crane.

The steel panels for the road girders are manufactured in Italy and then shipped from Livorno to Sines, Portugal. Here they are processed into bridge sections, which are floated to Aalborg (Northern Denmark) and welded together into complete bridge spans.

3. The combined road and railway bridge crosses the western channel between Funen and Sprogø. This west bridge is a 6.6-km-long all-concrete bridge with separate decks for rail and highway traffic. The bridge consists of six continuous bridge sections of a length of about 1100 m; the individual bridge sections are linked by expansion joints and hydraulic dampers that transmit only instantaneous forces.

The box girder underneath the rail track is only 12.3 m wide, compared to the roadway girder width of 24.1 m. However, the railway girder is 1.36 m deeper than the roadway girder.

The piers of the west bridge are founded on precast caissons. Each caisson receives two pier shafts, one for roadway girder, the other for railway girder. Each of the 110.4-m-long girder elements is cast in fixed steel shuttering in five sections. These sections are progressively linked by prestressing at the precasting yard. A special vessel, *Svanen,* a self-propelled floating crane with a lift capacity of 7123 tons, was used to transport the foundation caissons to the relevant position, to lift the pier shafts into place and to place the 110 m long girders on the top on the pier shafts.

In addition to the bridge and tunnel sections, the Great Belt fixed link, opened to traffic in 1998, also includes new road and railway sections on land, connecting the existing highways and railways with the fixed link.

64.5.3. Tagus River Bridges

The Tagus Bridge, also named the Vasco da Gama Bridge, is a 17.2-km-long structure connecting the northern and southern banks of the Tagus estuary. This project will solve a great part of the traffic problems in Lisbon by creating a link between new highway systems in the north and in the south of the city, and makes the traffic flow more easily between the northern and the southern parts of Portugal (Figure 64.36).

The Vasco da Gama project is divided into seven distinct sections, five of which are bridges and viaducts, representing 12.3 km.

1. The northern viaduct, with a total length 488 m of 11 spans, crosses the northern railway line of the Portuguese Railway Company (C.P.) and several local junctions. The deck width is variable to accommodate connection to local roads by slip roads. Span lengths vary from 42 to 47 m. The deck, 3.50 m deep, is cast *in situ* span by span. The typical span is 29.3 m wide and made up of four T-shaped concrete beams.

2. The Exhibition viaduct, with a total length 672 m of 12 spans, is also situated on the northern bank of the Tagus. It crosses the area where the 1998 World Exhibition took place. The bridge span lengths are the following: 2 × 46.2 m, 3 × 52.3 m, 55.3 m, 6 × 61.3 m. The deck, 29.3 m wide, is made up of twin prestressed concrete box girders, connected by the upper slab. Each box girder consists of precast segments put in place by mobile cranes using the balanced cantilever method. After pouring the cantilever closure joints, external prestressing is tensioned inside the box girders to ensure deck continuity.

The deck is supported by concrete piers founded on 1700-mm-diameter piles through a 4.5-m-thick concrete pile cap.

3. The main bridge is a cable-stayed bridge, 829 m long with a 420-m-long main span. The H-shaped pylons are founded on 2.2-m-diameter piles; these 44 bored piles are 53 m long. A very stiff and robust pile cap allows the foundation to withstand impact from a 30,000 ton vessel traveling at 8 knots.

The pylons comprise two legs and reach a height of 150 m. These legs, with a cross section varying from 12 × 7.7 m to 5.5 × 4.7 m, are slip formed. They are linked by a 10-m-deep prestressed box girder at base level, and by a transverse cross beam 87 m above the base, poured *in situ* in four stages. The upper part of the pylon, above the cross-beam, consists of a composite steel–concrete structure in which stays are anchored.

The deck, 31.28 m wide, consists of two longitudinal 2.50-m-deep and 1.30-m-wide concrete girders, connected every 4.4 m by 2.0-m-deep steel cross-beams. This composite structure is completed by a 25-cm concrete top slab (Figure 64.37). The 8.83-m-long deck segments are cast *in situ* using traveling formworks by the balanced cantilever method. Two points should be noticed: during segment concreting the final stays are used as temporary stays and the traveling formwork is designed to pass beyond the rear piers.

Like all the other structures, the main bridge is designed to withstand violent earthquake effects without damage. Consequently, there is no fixed link between the deck and its supports. Dampers are installed, steel dampers transversely, and longitudinally steel dampers outfitted with hydraulic couplers. On top of that, damping guide deviators are placed at each end of the cable stays.

4. The central viaduct is 6531 m long of 80 spans and cross the Tagus estuary above sandbanks and two shipping channels. The deck for the most part of its length is less than 14 m above sea

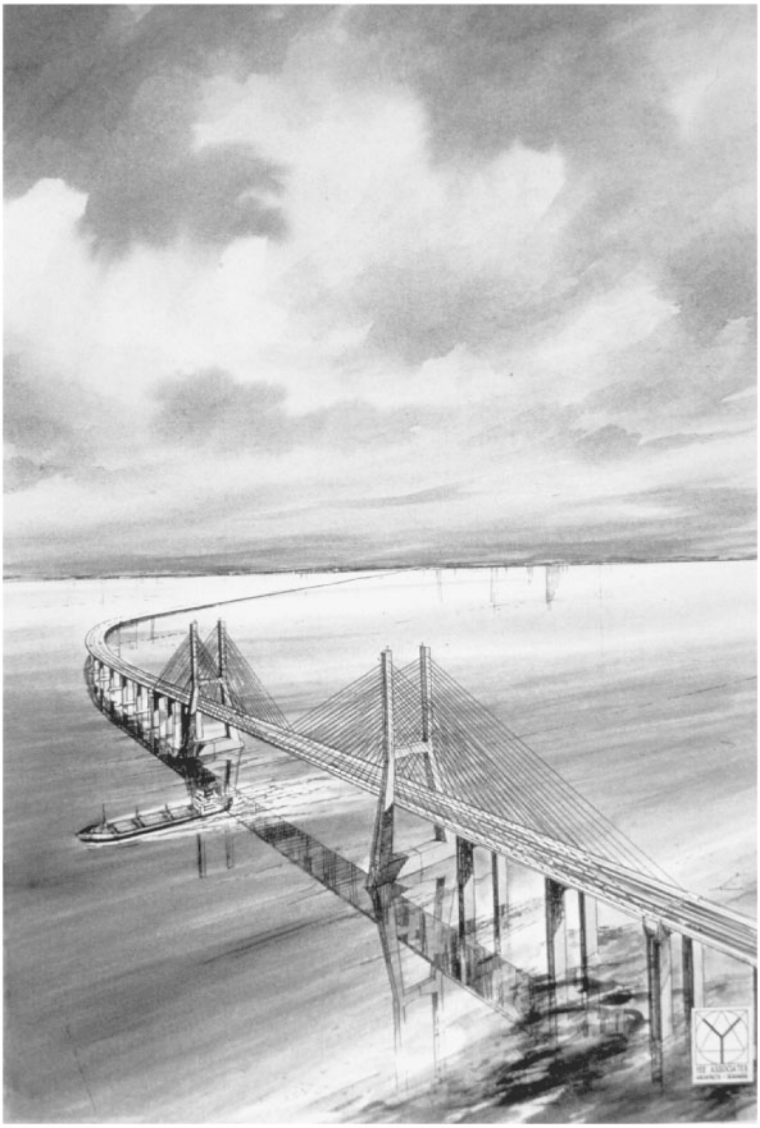

FIGURE 64.36 Tagus Bridge — artist's view. (Courtesy of Campenon Bernard.)

level. The typical span is 78.62 m long, but over the two shipping channels the span length rises to 130 m and the height above sea level rises to over 30 m. The viaduct span lengths are the following: 79.62 m, 3 × 78.62 m/93.53 m, 130.00 m, 93.53 m/60 × 78.62 m/93.53 m, 130.00 m, 93.53 m/11 × 78.62 m.

The deck, 29.3 m wide, consists of two parallel prestressed concrete box girders with two webs of constant height of 3.95 m, connected by the upper slab. Over the shipping channel, the girder depth is variable from 3.95 m at midspan to 7.95 m on piers.

Every span is precast in eighths; these segments, with a unit weight about 240 tons, are assembled on a bench by prestressing after adjustment. Each 1800 ton to 2000 ton girder is lifted and stored by a gantry crane with 2200 tons capacity load.

To transport and place the girders at up to 50 m above sea level, a special catamaran is used, equipped with two cranes with a capacity of 1400 tons at a radius of 25 m, 82 m tall. The rhythm of transport and placing is at a standard rate of one beam every 2 days. Prestressing cables ensure

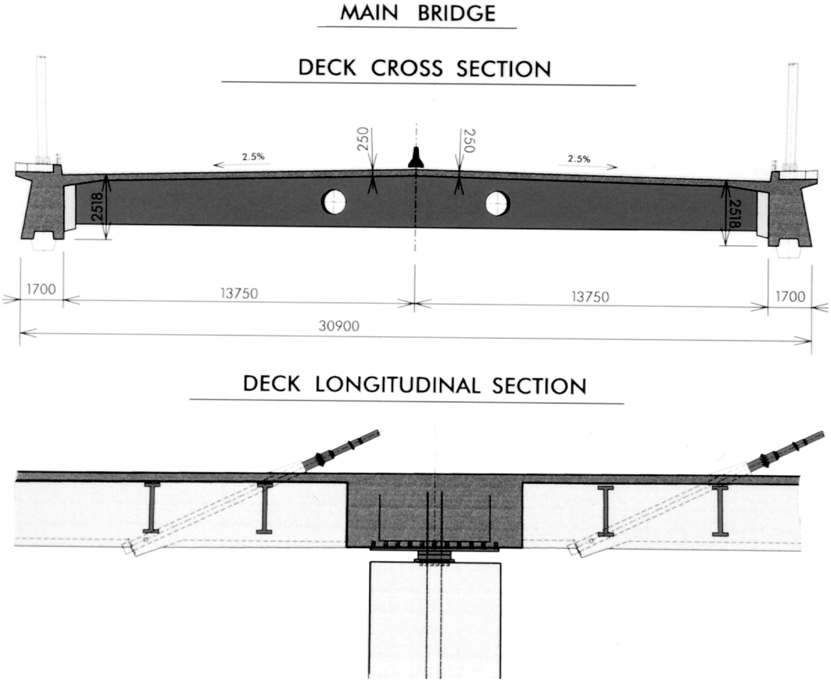

FIGURE 64.37 Tagus Bridge — main bridge deck cross section. (Courtesy of Campenon Bernard.)

longitudinal continuity of the deck. After concreting of continuity slab between the two parallel box girders, the transverse prestressing cables are tensioned. The deck is supported by concrete piers founded on 1700-mm-diameter deep piles.

5. The southern viaduct comprises 85 spans, each 45 m long, totaling 3825 m. As in the northern viaduct, the deck is composed by four T-shaped 3.50-m-deep concrete girders. The deck is cast *in situ* span by span with four mobile casting gantries working above the deck on two casting fronts. The deck is supported by concrete piers founded on bored piles for the land piers and on driven piles for the river piers.

The Vasco da Gama Bridge construction began in February 1995 and was finished in March 1998. It was privately financed and represents a cost of approximately $ 1 billion.

64.6 Future European Bridges

Future trends in bridge design can be classified in four categories:

1. Development of existing materials
2. Development of new materials
3. New structural association of materials
4. Structural control

1. The main materials used for bridges — concrete and steel — are still under development; their strength is always increasing. High-performance concrete (HPC) has been used for bridges for the first time in France and in the Scandinavian countries. Concrete with a compressive strength of 60 MPa (cylinder) at 28 days is becoming common for large bridges, especially for long spans and high piers. However, the advantage of HPC is not only strength, but durability, because this concrete is much more compact and much less porous than ordinary concrete. A new type of concrete called reactive powder concrete (RPC) is being developed in France; its compressive strength at 28 days can reach 200 to 800 MPa. It is meant to be prestressed and does not include any passive reinforcement. High-strength steel with yield stress of 420 to 460 MPa has been used for bridges in Germany, Finland, France, Luxembourg, Norway, the Netherlands, and Sweden. It is used mostly for long-span bridges, and for parts of the bridge that are submitted to high concentrated forces.

2. New composite materials are being developed for bridges in Europe. The main ones are:

- Glass fiber–reinforced plastic (GFRP),
- Carbon fiber–reinforced plastic (CFRP),
- Aramide fiber–reinforced plastic (AFRP).

Their main advantages are high corrosion resistance and light weight, whereas they are still more expensive than steel.

GFRP bars and cables have been developed since 1980 in Germany, in Austria, and in France. At least five bridges have been built in Germany using GFRP prestressing cables. The Fidget Footbridge in England includes GFRP reinforcing bars. CFRP stays have been used in Germany. AFRP stays have been used for pedestrian bridges in Holland and in Norway.

New composite materials have also been used for the deck structure itself: Bends Mill movable bridge in England, Arnhem Footbridge in Holland. The Aberfeldy Footbridge, in Scotland, is the world's first all-composite bridge: deck, pylons, and stays.

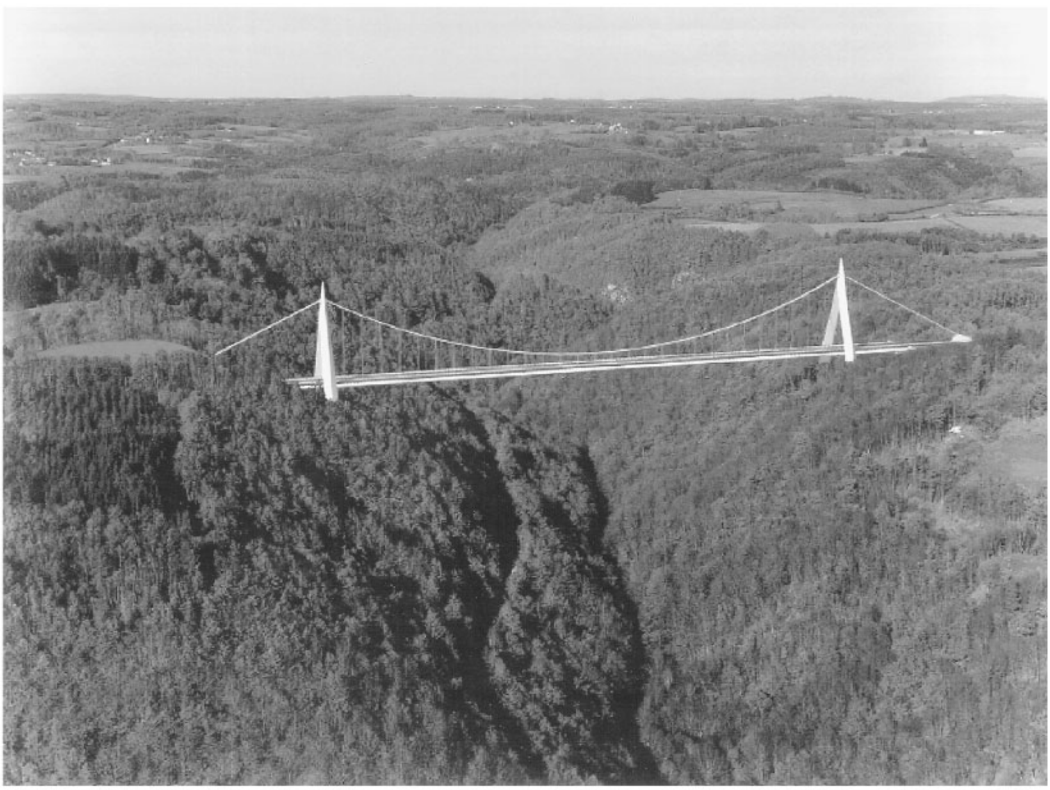

FIGURE 64.38 Chavanon Bridge. (Courtesy of Jean Muller International.)

3. The association of steel I-girders with a concrete slab has become very common for medium-span bridges. We think that this association of steel and concrete will be developed for a large variety of composite structures in the future: truss decks, arches, pylons, piers. A number of such innovative projects have been built in France and Switzerland, for example. The use of each material to its best capability will lead to more efficient and economical structures. A significant example of such a structure is implemented on the highway A89 which will link Clermond Ferrand to Bordeaux in southern France. To cross the deep valley of the River Chavanon respecting the natural environment, a suspension bridge is being built (Figure 64.38). The bridge deck is a steel concrete composite structure 22.4 m wide and 3.0 m deep. It is suspended by a single plane of suspension cables located at the cross section axis. The inverted V-shaped pylon straddles over the deck and leaves it free of any support. Its top is 52 m above the deck. This bridge, with a 300-m-long main span is an innovative, efficient, and very aesthetic projec**4.** With the development of high-strength materials, and possibly lightweight materials, bridges will become more and more slender and light, hence more sensitive to fatigue and dynamic problems, especially for long-span bridges. Consequently, it will become necessary to control vibrations due to traffic loads, wind, and earthquakes. This control can be achieved through passive devices, such as dampers, and active devices such as active prestressing tendons, active stays, active aerodynamic appendages. This will be the road toward "intelligent" bridges of the future...

An existing bridge could easily be equipped with an active device. Such a device was implemented in the Rogerville Viaduct, opened to traffic in 1996, located in northern France, on highway A29 not far from the Normandie Bridge (Figure 64.39). It is a continuous steel box girder, placed across the expansion joint, between two adjacent cantilever arms (Figure 64.40). It rests on two diaphragms on either side and may be adjusted before the bridge is opened to traffic to transfer shear force and bending moment, and consequently to compensate subsequent effects of steel relaxation and concrete creep. At the moment, the continuity girder is a passive device

This connection could be equipped to transfer (long term under dead load, and short term under live load), shear force and moment in an active fashion at all times (Figure 64.41). In other words, the magnitude of shear load and moment across the joint may be monitored and adjusted at the designer's request to restore all the geometric and mechanical properties of a continuous deck across the expansion joint.

FIGURE 64.39 Rogerville Viaduct. (Courtesy of Jean Muller International.)

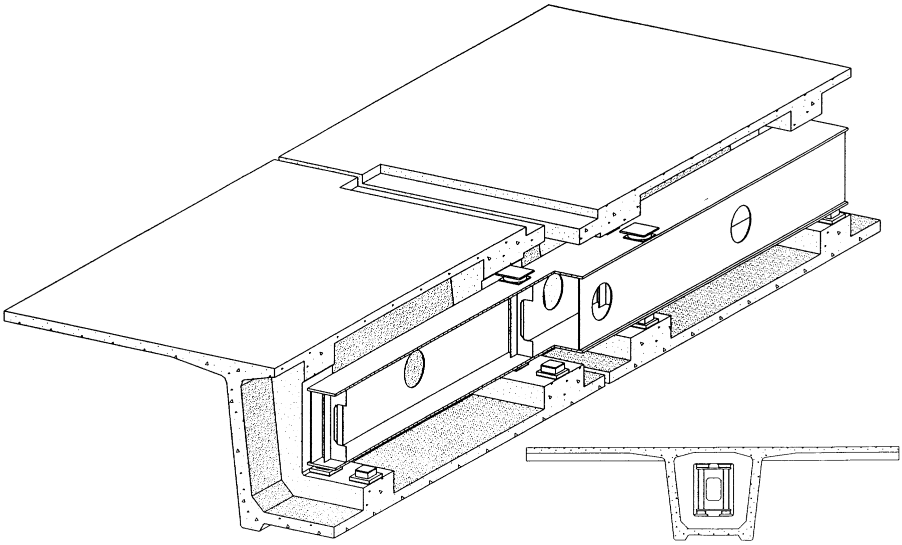

FIGURE 64.40 Rogerville Viaduct — expansion joint device. (Courtesy of Jean Muller International.)

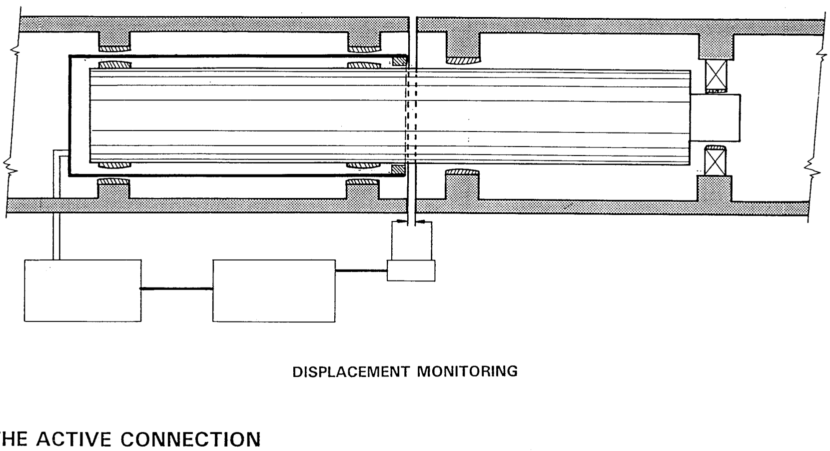

FIGURE 64.41 Active connection. (Courtesy of Jean Muller International.)

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