



## 1st International Symposium on Bridges and Large Structures

# Fixed Links and Long Span Bridges

## The new challenges of Structural Engineering

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### SUMMARY

Challenges for the new millennium will lead unavoidably to the construction of long links and long span bridges which will reduce the distances between people, the cost of transportation and the necessary time to travel around the world.

Several major fixed links, including exceptional long span bridges, have been built during the last fifteen years. The concept of cable-stayed bridges has considerably extended the field of Structural Engineering to the design of many crossings which were not possible in the past.

Structures to be built in the future will be gigantic, impressive, light and heavy, deep and high, wide and long. They will be challenging major straits, mitigating natural disasters, fighting the power of the wind, of the sea, of the earth, but linking people, countries, continents. They will have to be erected within a short time to improve our daily life as quickly as possible.

The way this is going to be achieved can be seen from the progress made in design and construction methods. Gigantism is not a fact; it is a need to erect major links, quickly, economically, and safely.

### KEYWORDS

Gigantism, Fixed Links, Cable-Stayed Bridges, Heavy Prefabrication and Placing Equipment

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## 1. Introduction

As shown in the previous part of this document, pre-assembly of typical prefabricated segments, leading to the progressive placement of large components and shorten construction period, was the result of a search for feasibility, erection speed and quality [1].

Indeed, competition, between huge and small precast concrete components to build the large bridges which were needed everywhere in the world, started at the end of the seventies. Building bridges by using heavy precast units and a powerful moving, lifting and placing equipment, a technique which associates the basic principles of prefabrication and displacement methods, lead in the last ten years to the completion of several gigantic and impressive links built at a pace never reached before.

At the same time, the extension of traditional construction processes to the construction of long span cable-stayed bridges, progressively made some of these links feasible at a reasonable cost, as long as it was possible to eliminate expensive supports in deep water and provide the required clearances.



**Figure 1 : The StoreBælt**

Within less than ten years, several major fixed links (Figure 1) associating short span bridges to medium or long span bridges were built in adverse environments thanks to the power of engines, computers and communication technology.

## 2. The Confederation Bridge (P.E.I – Canada)

The Prince Edward Island (P.E.I), is located south of Gulf of St Lawrence, east of New Brunswick, mainland Canada,

The concrete bridge structure, joining the island and the mainland, crosses the Northumberland Strait at its narrowest point; it is about 13 kilometres long [1].

Due to the unusual characteristics of the Northumberland strait, which is jammed with ice between December and April, the bridge is probably the longest bridge in the world across ice-covered water and both design and construction of the new crossing have had to take into account the extremes of weather that are experienced in this region of North America.

The bridge (Figure 2) consists of seven approach spans on the Prince Edward Island side of the crossing, with a total length of 555 meters, forty five marine spans, including the navigation span, with a total length of 11,080 meters, and fourteen approach spans on the New Brunswick side of the crossing, with a total length of 1,275 meters.



Figure 2 : Main section of the Confederation Bridge

The construction of the bridge and associated facilities started in spring of 1994 and the bridge was open to traffic in June 1997.

## **2.1. Approaches**

In the near-shore area, water depths of less than approximately 8 meters required short approach span lengths.

The shallow water depth limits construction access such that equipment and methods, that allow placement of spans up to 93 meters in length only, were utilised.

### **2.1.1. Design**

Each span consists of a slope webbed concrete box girder which varies from 5.06 m to 3.00 m in depth.

Each support pier for the approach spans consists of a 3.6 m x 5.2 m hollow rectangular concrete shaft on a conical pile cap and six shear key piles to withstand horizontal ice loads.

### **2.1.2. Construction**

Foundations and Ice shield of the approach piers were mainly constructed from an embankment using the ice shield steel skin as a cofferdam.

The approach decks consist of classical precast segments and these elements were placed with a movable launching gantry.

## 2.2. Main Bridge

In order to limit the number of piers located in the strait, the marine spans of the bridge are typically 250 meters long, with the exception of the first marine spans on both the Prince Edward Island and New Brunswick sides, which transition into the approaches and are therefore 165 meters in length.

In addition, the dead weight of the huge concrete box girder supported by the piers makes them more stable with regard to the high horizontal forces generated by the ice.

As a result, it also made it possible to precast fully the whole main bridge structure including pier bases which could accordingly rest directly on the sandstone at the sea bed level.

### 2.2.1. Major Characteristics

Each span consists of a variable depth concrete box girder measuring 14.00 m in depth at the pier locations, and tapering parabolically to 4.50 m at mid span.

The box width varies from 5 meters at the bottom of the section to 7 meters at the top.

The support piers consist of an 8 meters diameter hollow octagonal concrete shaft, varying in height up to 45.8 m. The top of the shaft is joined rigidly to the superstructure (Figure 3).



**Figure 3 : Confederation Main Bridge – Concept and Prefabricated units**

To protect against ice forces, the pier shafts are connected to an ice shield at water level to assist in the breaking and deflecting of ice located between 4 meters below to 3.5 m above mean sea level.

The pier shaft and the ice shield sit on a circular or oval, conical shaped footing.

The footing is situated on a tremie concrete base placed on a founding surface dredged down to bedrock.

### **2.2.2. Conceptual design**

Construction started in the fall of ninety three and continued until ninety seven. It emphasised the necessary interaction between design and construction technology for this type of fast track project.

The 43 repetitive 250 meter spans are composed of four typical prefabricated units referred to as: pier base, pier shaft, main girder, hinged drop-in or fixed drop-in, these units being prefabricated in segments separated by casting joints (Figure 3).

Thus, the completed structure is composed of portal frames, each with two cantilevers, the tips of these cantilevers being simple supports for the 60 m hinged drop-in units.

A typical pier base consists of 22 meter diameter and 4 meters wide ring footing. The conical shell is connected to a barrel which varies in height according to the depth of the foundation.

The barrel ends at elevation 4 meters below mean sea level and is topped by a male cone to connect the pier shaft with the pier base. The weight of these units varies from 3700 tons to 5100 tons.

Each pier shaft consists of the ice shield and the shaft itself.

The ice shield is conical with base diameter of 20 meters and height of 8 meters with 52 degree angle to break ice flows and was constructed using either a 10 millimetres thick steel sheet or 100 MPa concrete for abrasion protection.

The pier shaft varies from an octagonal shape at the top of ice shield to rectangular at the top of shaft.

The top of pier shaft was equipped with a template (100 tons) which is match cast to the soffit of the main girder.

A typical marine span was constructed as a 192.5 m long double cantilever unit.

Each is made of eighteen line cast segments: a 17 meters long pier segment, eight segments on each side of the pier segment varying in length from 7.5 m to 14.5 m and a corbel (on one end only).

The drop-in span is either 52 meters long to connect the two cantilevers rigidly to create a frame or is a simply supported 60 meters girder to close the gap between two consecutive frames.

### **2.2.3. Prefabrication**

The construction method consisted of constructing the major structural elements at a precasting yard prior to placing them in deep water.

The precasting yard was arranged in four production lines (Figure 4).

Six pier bases were fabricated simultaneously and up to sixteen stored in the yard.



Four pier shafts were constructed simultaneously and eight completed units could be stored.

All segments of a main girder were fabricated in ten fixed locations in the assembly yard.

The pier segment was always cast at the same location before being transported transversely to the first line until it aligned with the first two forms. These two segments were cast, one on each side, cured and post-tensioned.

The completed assembly of pier segment and the first two segments was moved transversely to the second casting line. The same procedure and assembly operation was repeated eight times, the corbel being constructed in the storage area.

All precast units were being moved from the yard storage area to the load out jetty facility using Huisman Sliding Systems.

The structural units were "slid" directly out of storage in the staging area and onto the jetty using tracks of stainless steel and Teflon and a hydraulic pushing system.



Figure 4 : Casting Yard

#### 2.2.4. Marine operations

Marine operations included preparation of the sea bed, delivery and erection of the precast elements.

##### **Pier Base Dredging**

The pier locations were dredged to competent bedrock, as required, by a clamshell dredge with a heavy-duty bucket.

A special rock bucket was used to dredge a trench into the bedrock corresponding to the geometry of the ring footing of the pier base. The dredged rock surface was then swept clean of any remaining soft material using high pressure, high volume water jet pumps.

##### **Delivery of Precast Elements**

A heavy lift floating catamaran crane was then used to lift the substructure and the superstructure units off the jetty and carry them out to the Strait where they were positioned and placed in their permanent location.

The catamaran type vessel, called the Svanen, was previously used at a similar construction project in Denmark (Storebaelt).

Due to the much larger precast elements used in the Northumberland Strait Crossing, the Svanen required extensive modification prior to being brought to site.

### **Pier Base Erection**

Each pier base was picked from the staging area jetty and transported to the bridge site by the heavy lift floating crane.

The Svanen was positioned adjacent to the pier location, and lowered the base onto three prepared support points which were precisely located and levelled. The trench below the foot of the base was thereafter filled with tremie concrete ensuring the bottom of the pier base had complete contact.

### **Shaft Erection**

The pier shaft/ice shield element was similarly transported from the staging area by the Svanen and lowered into place until it rested on hydraulic jacks on top of the pier base.

Once the pier shaft had been positioned, it was accurately levelled and then made monolithic with the pier base with a closure joint and continuity post-tensioning.

The top of the shaft was then prepared to receive the main span. This was achieved by the use of a precast alignment template which was accurately surveyed and grouted in place.

### **Main span installation**

The 7800 ton main span girder unit, 192.5 m long, was picked from the staging area jetty and transported to the appropriate bridge site location.



**Figure 5 : Placing of a main girder**

The Svanen was positioned adjacent to the completed pier shaft (Figure 5), and placed the main span.



The precast template which was earlier placed on the top of the pier shaft had match cast shear keys which fitted exactly into the underside of the main girder.

Vertical steel pilot guides were bolted on four corners to help position the unit exactly as it was lowered the final 0.50 m. As the girder was lowered the final 0.50 m its swaying motion was slowed and then stopped by a dampening system so that the keys align and match.

The Svanen was then released and final continuity post-tensioning tendons were installed and stressed, to create a moment-resisting connection between main girder and pier shafts.

### **Drop-in-Span installation**

The mid-span sections were installed using a drop-in girder method (Figure 6). There were two types of drop-in girder: 60 meter expansion girders and 52 meter continuous girders.

The Svanen picked and transported the mid-span girders similarly to the other components. Special temporary top slab post-tensioning had to be applied to allow this element to be lifted as a double cantilever instead of simple span. The Svanen raised the mid-span girder above the adjacent pre-placed cantilevered girder segments, aligned it within the gap, and lowered it into place.



**Figure 6 : Drop-in-Span installation**

In the case of the continuous girder, horizontal jacking was applied across the closure joints to ensure stability of the structure as the load was lowered.

The fixed drop-in unit was made continuous at its ends by externally prestressed tendons connecting it to the two adjacent main girder units.

### 2.2.5. Experience gained in the field of deep water crossing

#### **Prestressing of the Deck**

As mentioned before, intensive use of prestressing tendons was a key factor of the assembly of all the components of the main bridge. 13000 tons of prestressing strands were necessary for the completion of the bridge.

The deck is prestressed longitudinally and transversely. Longitudinal tendons located in the deck of the main bridge are many and big units.

Consequently, the top and the bottom gussets are congested areas. Moreover, due to the unusual length of the segments cast in place at both ends of a main girder being prefabricated and moved at each stage in the yard of the P.E.I. staging facility, it was necessary to anchor two pairs of tendons in the joints and full scale testing to design the steel reinforcement had to be carried out.

#### **Speed of Erection and Progress on Site**

It has to be mentioned that, in August 2006 and therefore in one month, two additional kilometres of the bridge have been prefabricated and erected in the Northumberland Strait including foundation preparation and completion.

## **3. The Vasco de Gama Bridge**

The Vasco de Gama bridge, over the Tagus River in Portugal (Figure 7), was completed at the beginning of year 1998. The bridge, 12.3 kilometres long, 30 metres wide, crosses the Tagus at a location where the river is about 10 kilometres wide.

It consists of a succession of five different concrete bridge structures:

- the North approach viaduct, 488 metres long ;
- the Exposition Viaduct, 672 metres long ;
- the Main Bridge, 820 metres long ;
- the Central viaduct, 6531 metres long ;
- and the South approach viaduct, 3825 metres long.

which have been built using four different construction methods.

### **3.1. Approaches and Access Viaducts**

The North and South approaches, very similar, were cast in place on a movable set of form-works. This construction method is still intensively used in Portugal but it is a fact that this is a very economical technique as long as it applies to open deck cross sections. In addition to that, this type of bridge structure allows designing bridges of variable width.

The Exposition viaduct (with reference to the 1998 Universal Exhibition) was built using prefabricated segments placed by means of a powerful crawler crane with a lifting capacity of 600 tons at a height of 50 metres and the Segmental Construction method was also applied to the two parts of the central viaduct located above two secondary navigation channels.

### 3.2. Cable-Stayed Bridge

The deck of the cable-stayed bridge connects the expo-viaduct to the central viaduct and crosses the major navigation channel of the Tagus, with a main span 420 metres long. It was cast in place using form travellers although the construction started with the prefabrication of the first segments on the North bank of the river. These segments were then placed on an intermediate platform between the legs of the pylons. The form travellers were installed and the two adjacent segments were cast.



Figure 7 : The Tagus fixed link

At this stage, these three first segments weighing 2.000 tons were lifted by strand jacking and the corresponding cable-stays were stressed. Typical segments, 8.83 metres long were then cast symmetrically in the form travellers with a cycle of one week.

The central viaduct, which is located in between the main bridge and the south approach viaduct, is made of nine sections of nine spans 78.6 metres long, each span consisting of twin prefabricated box girders connected by a concrete strip cast in situ.

The precasting yard, located 20 kilometres from the site, was designed to allow the fabrication and the placing of one girder 77.6 metres long weighing 2000 to 2200 tons every two days. For this purpose and to give the necessary flexibility in the whole production line of the girders, critical stages were disconnected and each girder has been cast in eight segments, 100 cubic metres each.

Finally, the girders were placed with a catamaran barge, 76 metres long, 68 metres wide, 90 metres high, moved by four revolving propellers, impressive heavy lifting equipment able to place and move 2.200 tons at 50 metres in height.

## 4. Development of Cable-Stayed Bridges

Over the last 30 years, cable-stayed bridges have become more common and better appreciated by architects, engineers and the public all around the world. This paper examines the roots of that increasing popularity, particularly in Europe and the United States.

Unlike some other bridge types, cable-stayed bridges offer a large variety of appearances. This flexibility often results in more attractive structures that can instantly become a signature landmark in a city or community. Cable-stayed bridges in Europe and the United States also drive innovation in pylon design and in both cable arrangement and deck material in conjunction with construction methods. The goal in these cases is to use the right material at the right place, while making the cable-stayed structure as simple as possible.



#### 4.1. Prestressed Concrete Cable-Stayed Bridges

The first modern cable-stayed bridges consisted of steel decks built using free cantilever construction, supported by a small number of stay cables (Figure 8). The idea was to make long spans feasible by replacing expensive intermediate supports by active supporting cables. As a result:

- Stay cables were big units generating large forces at anchorages
- Steel deck had to resist large bending moments during erection



Figure 8: From few to many cables – Oberkassel Bridge (left) & Bonn-North Bridge (right)

Using smaller cables regularly distributed along the deck (Figure 8 - Right) was therefore a major improvement as it was then possible to optimize the span-to-depth ratio of the deck structure. In addition, the idea rapidly appeared as being an extension of the classical post-tensioned tendon layout of concrete bridges, in which PT tendons are placed outside the concrete deck with increased eccentricities.

##### 4.1.1. The Pasco-Kennewick Bridge (Washington State – USA)

The Pasco-Kennewick Bridge<sup>1</sup> over the Columbia River in Washington State supported its centre span of 299 meters (980 feet) from two double concrete towers, the cables fanning down to the concrete deck on either side of the roadway (Figure 9).



Figure 9: Pasco-Kennewick Bridge<sup>2</sup>



Figure 10: Brotonne Bridge

<sup>1</sup> Designed by A. Grant & Associates in collaboration with Leonhardt und Andrä

<sup>2</sup> Courtesy of Holger Svensson (Leonardt, Andrä und Partner)

Completed in 1978, the cable stayed portion of this continuous bridge had unique features that made it remarkable at that time. It was:

- Fully suspended between the two back piers
- Made of precast segments weighing 270 tons and erected according to the classical balanced cantilever method from the towers
- Relatively slender as the span to depth ratio was about 140

This set of major characteristics produced a world record in the field of prestressed concrete bridges.

#### **4.1.2. The Brotonne Bridge (France)**

The Brotonne Bridge<sup>3</sup> over the Seine River in Normandy was completed and opened to traffic in July 1977 [3] [4]. It also had a number of unique distinctions, including:

- A main span 320 meters (1050 feet) long (Figure 10)
- A single box girder deck, 19.20 meters wide, consisting of 20-cm-thick thin prefabricated webs, a bottom slab, a top slab and two internal struts cast in place
- Two axial pylons and axial cable planes

Segments were typically 3 meters long and made in a relatively light form traveller stiffened by the previously placed precast web panels.

The cables consisted of seven wire PT strands encased in a steel pipe and grouted after tensioning operations. They pass through the pylons and are anchored at the top of the struts in a complicated concrete block.

#### **4.1.3. The Coatzacoalcos Bridge (Mexico)**

The Antonio Dovali Jaime Bridge<sup>4</sup> over the Rio Coatzacoalcos, built in the early 1980s, has a main span 288 m long. The deck is quite similar to the deck of the Brotonne Bridge, while:

- Segments, typically 3.53 meters long, were cast in place in form travellers
- External PT tendons (Figure 11) equilibrated the vertical component of the force generated by the cables in internal struts
- The concrete deck is built in two gracefully shaped inverted Y pylons (Figure 12).



**Figure 11 : PT tendons equilibrating tension in the struts**

The complex sets of bearing pads between the pylon base and the deck were therefore eliminated as well as the complicated conjunction of heavy reinforcement and cable-tendon intersection at the top of the struts.

<sup>3</sup> Designed by J. Muller and Campenon Bernard design team

<sup>4</sup> Designed by Sogelerg (France) in collaboration with Jacques Combault.





Figure 12: Coatzacoalcos Bridge



Figure 13: Sunshine Skyway Bridge

#### 4.1.4. The Sunshine Skyway Bridge (Florida –USA)

The Sunshine Skyway cable-stayed bridge<sup>5</sup> has about the same configuration as the Brotonne Bridge with a centre span 1200 feet (366 m) long.

The most prominent features of this outstanding structure (Figure 13) were the engineering and erection assembly of the superstructure elements:

- The pylons are 240 feet high
- The deck is 95 feet wide and rests on twin pier shafts at pylon locations
- The cable-stayed span was built using large prefabricated box girder segments and combining balanced cantilever with stay cable erection

The cable concept is the same as the one successfully used for the Brotonne bridge and the Coatzacoalcos bridge and the anchoring concrete block of the stay cables has been simplified by the use of external PT tendons to equilibrate tension forces generated in the internal stiffening struts.

#### 4.1.5. The Iroise Bridge (France)

The Iroise Cable-Stayed Bridge over the Elorn River<sup>6</sup> has a main span 400 meters (1310 feet) long. When completed in 1994, it was the longest bridge with a single plane of stay cables.

The bridge is 800 m long (Figure 14); it is symmetrical and the two pylons are 83 meters (272 feet) high.

The deck, 23.10 meters (76 feet) wide, is 3.50 meters (11.5 feet) high. It consists of a rectangular concrete box with internal and external struts. Several conceptual aspects are worth mentioning:

<sup>5</sup> Designed by Figg and Muller Engineers; photograph courtesy of Parsons Brinckerhoff

<sup>6</sup> Conceptual design: Michel Placidi.

- The side spans are made of normal concrete while the major part of the main span is made of lightweight concrete. From this point of view, it is a hybrid structure
- Cables are anchored in the deck and the pylons
- In the pylons, the cables are anchored in a composite pylon head made of a steel box embedded in high performance concrete
- In the deck, internal struts consisting of steel barrels, 150 mm in diameter, are only provided at cable anchorage locations (i.e. every 6.78 meters); they support the top slab through a central  $\Pi$  shaped beam
- Segments of the main span were cast in-situ and typically 6.78 meters (22 feet) long
- The effect of the steel strut expansion generated by stay cable tensioning were reduced by casting the concrete anchoring blocks inside the central beam after the rest of the top slab

#### 4.2. *Small and Medium Span Concrete Bridges*

Cable-stayed structures were developed while the demand for long span bridges grew. But there are many ways of using them in other circumstances – mainly when both the design and construction process can take advantage of their many possibilities

The Meylan pedestrian bridge<sup>7</sup> over the Isere River (France) is a good example of what can be achieved in the field of small-span cable-stayed bridges when the concept of the structure greatly simplifies the erection process. The main features of this small bridge (Figure 15) are the following:

- The three-span symmetrical structure consists of a triangular box girder, two inverted Y shaped pylons and cables made of PT tendons encased in cement grouted HDPE pipes
- The short side spans are built-in massive abutments
- The main span, 79 meters long, is made of lightweight concrete
- The structure was entirely cast in place in a falsework on the banks of the river and rotated to its final position after installation and tensioning of the stay cables

The original construction method, which was applied at the same time to the Illhof pedestrian bridge in France, also applied to medium-span bridges such as the Ben-Ahin bridge<sup>8</sup> (main span length: 168 meters) in Belgium

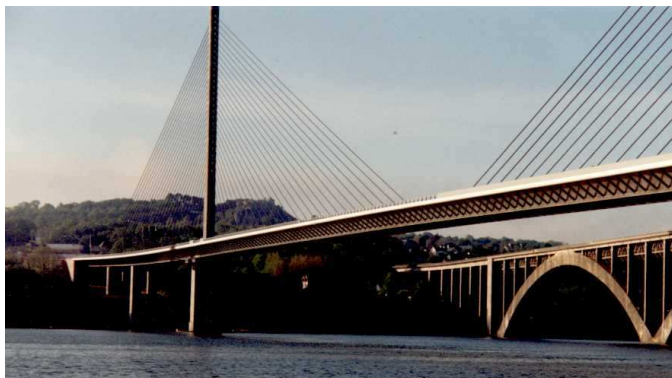


Figure 14: The Iroise Bridge



Figure 15: The Meylan Footbridge

<sup>7</sup> Design and Construction: Setra - Campenon Bernard.

<sup>8</sup> Structural Engineering: Greisch.

### **4.3. Long Span Composite Steel-Concrete Cable-Stayed Bridges**

Steel and concrete can be associated in various ways. This includes classic bridge types as well as cable-stayed bridges. To what degree steel and concrete can be used cooperatively depends on the width of the deck, the span arrangement and main span length, the number of cable planes and the available construction methods.

For a time after the Tacoma Narrows Bridge collapse, plate girder bridges were judged too harshly with regards to aerodynamic stability. The first significant composite cable-stayed bridge consisting of a concrete slab connected to twin steel plate girders was the Alex Fraser Bridge in Vancouver. It was only designed and built after comprehensive studies were conducted on the wind effect on suspended structures.

#### **4.3.1. The Second Severn Crossing (UK)**

Built in a severe environment, the cable-stayed structure of the Second Severn Crossing (Figure 16) carries three lanes of traffic plus an emergency lane in each direction. The main component of the crossing is a symmetrical cable-stayed bridge with a central span of 456 meters (1495 feet) formed from composite construction with steel longitudinal and transverse girders and a reinforced concrete slab. The two pylons are made of two hollow legs in reinforced concrete – except in the stay anchorage area where vertical and horizontal prestressing has been provided – braced by two cross beams.

The deck, 3.15 meters deep and 35 meters (115 feet) wide, has the following characteristics:

- The twin longitudinal plate girders, 2.5 meters deep, are braced every 3.65 meters by transverse truss beams
- The concrete slab connected to the beams is 20 to 35 cm thick
- The cables, consisting of seven wire strands embedded in HDPE duct filled with wax are anchored in steel boxes located at both ends of the cross beams

One of the most significant aspects of the bridge is the way it was built. The 7.30-meter-long deck elements were prefabricated full width on a pre-assembly bed, before being transported and bolted to the already-built cantilevers. A 2.00-meter-wide strip of the concrete slab was finally cast in place before tensioning of the cables.

#### **4.3.2. The Normandy Bridge (France)**

The Normandy Bridge (Figure 17) over the Seine River<sup>9</sup>, completed in 1994, earned the distinction of world's longest cable-stayed bridge, with a main span of 856 meters (2807 feet).

In 1999, the Tatara Bridge (Japan) took that record away with a main span 890 meters (2918 feet) long.

The Normandy's bridge deck, 21.20 meters (70 feet) wide and 3.00 meters (10 feet) high, is rigidly connected to the 202-meter-high (662 feet) inverted Y concrete pylons. It is made of a three-cell concrete box in the approach spans and the start of the centre span, while the major part of it consists of a single orthotropic steel box, the span-to-depth ratio being 285.

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<sup>9</sup> Conceptual design: Setra – Structural Engineering and Construction: Bouygues – Campenon Bernard & Cowi - Monberg and Thorsen.





**Figure 16: The Second Severn Crossing**



**Figure 17: The Normandy Bridge**

Designed to reduce detrimental wind effects on the main span, the deck cross section had to be adapted to both steel and concrete materials of this uncommon, but attractive type of composite superstructure. The unusual concept of the steel-concrete composite pylon head made it possible to anchor the two cable planes on a rather short length.

#### 4.3.3. The Clark Bridge (IL – USA)

The top-saddle, cable-stayed Clark Bridge<sup>10</sup> over the Mississippi River (Figure 18) has the following characteristics:

- The main span is 756 feet (230.60 meters) long
- The deck, a slab-and-girder floor system, is 108 feet (33 meters) wide
- The two cable planes are saddle-draped at the top of each pylon, which consist of a 283-foot (86.30 meter)-tall mast located on the roadway centerline

To reduce the obstruction of the bridge in the river, the design team used single pylons with supporting piers. The Clark Bridge also featured a combination of a dual plane of cable stays, which was the first time this method was used in the United States.



**Figure 18: The Clark Bridge**



**Figure 19: The Charles River Bridge**

The top-mounted common saddle provides for continuous stays, reduces the number of expensive cable anchorages and eliminates the splitting (tensile) forces in the concrete pylon that non-continuous stays imposed in concrete pylons. In addition, using a common saddle

<sup>10</sup> Designed By Figg Engineering - Hanson

mounted at the top of the pylon improves the efficiency of the stays by maximizing the stays' slope relative to the deck; the sloping planes of stays and the single pylon provides a beautiful structure, while the common saddle for the stays allowed for easier stay placement.

#### **4.3.4. The Charles River Bridge (MA – USA)**

Fully opened to traffic in December 2004, the new Leonard P. Zakim Bunker Hill Bridge<sup>11</sup> over the Charles River (Figure 19) is the only one of its kind ever built. In addition to being the widest cable-stayed bridge in the world, it is the first "hybrid" cable-stayed bridge in the United States, using both steel and concrete in its frame. The main span consists of a steel box girder and steel floor beams, while the back spans are made of post-tensioned concrete.

The Leonard P. Zakim Bunker Hill cable-stayed bridge features a 56.4-meter-wide, five-span hybrid superstructure with:

- A main span of 227 meters
- Short back spans
- Inverted Y shaped towers

The main span consists of precast concrete deck panels acting compositely with longitudinal steel box edge girders and transverse steel floor beams by means of cast-in-place closure strips. The box edge girders are supported by cables anchored on the outside web at 6.10-meter intervals. The back spans consist of multi-cell, cast-in-place concrete box girders, 3.00 meters deep and 38.40 meters wide. This includes a 3.00-meter-wide central spline beam with internal floor beam diaphragms located every 4.6 meters and framed with four secondary webs. The spline beam, in turn, is supported by a single plane of cables spaced at 4.60 meters.

#### **4.4. Exceptional Achievements and New Trends**

Exceptional achievements and new trends are mainly visible through the development of multi-span cable-stayed bridges and an incredible increase of span-to-depth ratios or main span lengths.

##### **4.4.1. The Rion-Antirion Bridge (Greece)**

Completed in 2004, few years after the Ting Kau Bridge in Hong Kong, the Charilaos Trikoupi Bridge (Figure 20) over the Corinth strait marks the beginning of the new millennium in the field of structural engineering [5] [6] [7] [8].

Made of three central spans, 560 meters long, and two side spans, 286 meters long, the deck of this exceptional bridge is a composite steel concrete structure. It is 27.20 meters wide and consists of a concrete slab, 25 to 35 cm thick, connected to twin longitudinal steel I-girders, 2.20 meters high. The girders are braced every 4.00 meters by transverse cross beams. It is continuous over its total length of 2252 meters (7385 feet) and fully suspended to the four pylon heads by eight sets of 23 pairs of cables in order to be isolated as much as possible from the ground motion during the strong seismic events that may occur in the area.

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<sup>11</sup> Bridge concept: Christian Menn (Switzerland)



#### 4.4.2. The Millau Viaduct (France)

Completed some months later, the viaduct over the Gard River valley (Figure 21) near Millau is also an outstanding multi-span cable-stayed bridge consisting of six main spans, 342 meters long, and two side spans, 204 meters long.



Figure 20: The Rion-Antirion Bridge



Figure 21: The Millau Viaduct

The continuous trapezoidal orthotropic steel deck, designed to resist wind forces, is 32 meters wide and 4.20 meters deep. It was incrementally launched from both sides of the valley by using temporary supports at mid span. Masts and stay cables were installed later before temporary pier removal.

#### 4.4.3. Other Major Achievements

The Skarnsundet cable-stayed bridge (Norway) has a world record main span of 530 meters. Due to the fact that the concrete deck is only 13 m wide, it is made of a triangular three web box, 2.13 meters deep.

The Evripos Bridge (Greece) completed in 1992, has a main span 215 meters long. It is made of a concrete slab, 45 cm thick, supported by two twin leg pylons and two cable planes. This leads to a fantastic span-length-to-depth ratio of 475.

The Bai Chay Bridge, recently completed in Vietnam, is a new world record in the field of prestressed concrete cable stayed bridges with single cable planes as the main span is 435 meters long.

The Stonecutters Bridge in Hong Kong will have, when complete, a main span 1024 meters long suspended to two single pylon shafts.

The world record in terms of centre span length is owned by the recently completed Sutong cable-stayed bridge in China. It has a main span 1088 meters (3567 feet) long. Its record is not likely to last, however. A new cable-stayed bridge with a main span 1200 meters long is already underway elsewhere in China.

The Golden Ears Bridge<sup>12</sup> over the Fraser River near Vancouver (BC – Canada), currently under construction, is a multi-span cable-stayed structure supported by four main river piers. This unusual hybrid cable-stayed structure (Figure 14) combines a steel-concrete composite

<sup>12</sup> Conceptual design: Buckland & Taylor Ltd in association with McElhanney Consulting Services Ltd, Trow Consulting Services Ltd and Leonard, Andrä und Partner GmbH.

deck and relatively flat harped cable-stays with low profile in such way that the bridge has a structural behaviour between that of a true cable-stayed bridge and an extradosed bridge.



Figure 22: The Golden Ears Bridge (Rendering view)<sup>13</sup>

#### 4.5. Conclusions

The development of cable-stayed structures is similar in North America and Europe. Its use is expanding very quickly and giving rise to many beautiful landmarks, while the field of extradosed bridges has yet to be fully explored on both continents.

Because they are easy to build with classical erection processes, using either cast –in- situ or precast segments quickly assembled, concrete cable-stayed bridges have been favoured in many countries as long as span lengths were in the reasonable range of 200 to 400 meters (600 – 1300 feet). In addition, time and experience has helped the industry improve several design details that have proven beneficial to the structural concept.

Concrete and steel are more and more judiciously combined to produce hybrid or composite structures because they are the right material at the right place in terms of weight and ability to support high compression forces or high tensile stresses.

For span lengths up to 600 meters (2000 feet), steel-concrete composite decks consisting of a top slab connected to twin plate girders braced by cross beams at a regular spacing are feasible, cost effective and often preferred to other concepts.

Beyond this limit of 600 meters, which is critical for aerodynamic stability reasons, the cable-stayed bridge decks are usually made of orthotropic steel boxes specifically designed to reduce and resist wind forces.

Due to the heavy loads they carry, the pylons are generally made of concrete, except in the cable anchorage zone where they more likely consist of a steel box embedded in the concrete structure of the pylon head, directly supporting the anchoring plates. Finally, for many

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<sup>13</sup> Courtesy of Don Bergman (Buckland and Taylor Ltd)

bridges, the cable-stay system uses basic components (high performance concrete and strands) originally developed for the post-tensioning industry, but improved for application to cable-stay technology.

These factors, taken together, naturally resulted in the increase of cable-stayed bridges throughout the United States, Europe, and the rest of the world, even though the promising field of extradosed bridges in terms of aesthetics and cost efficiency has not been fully investigated and developed yet.

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