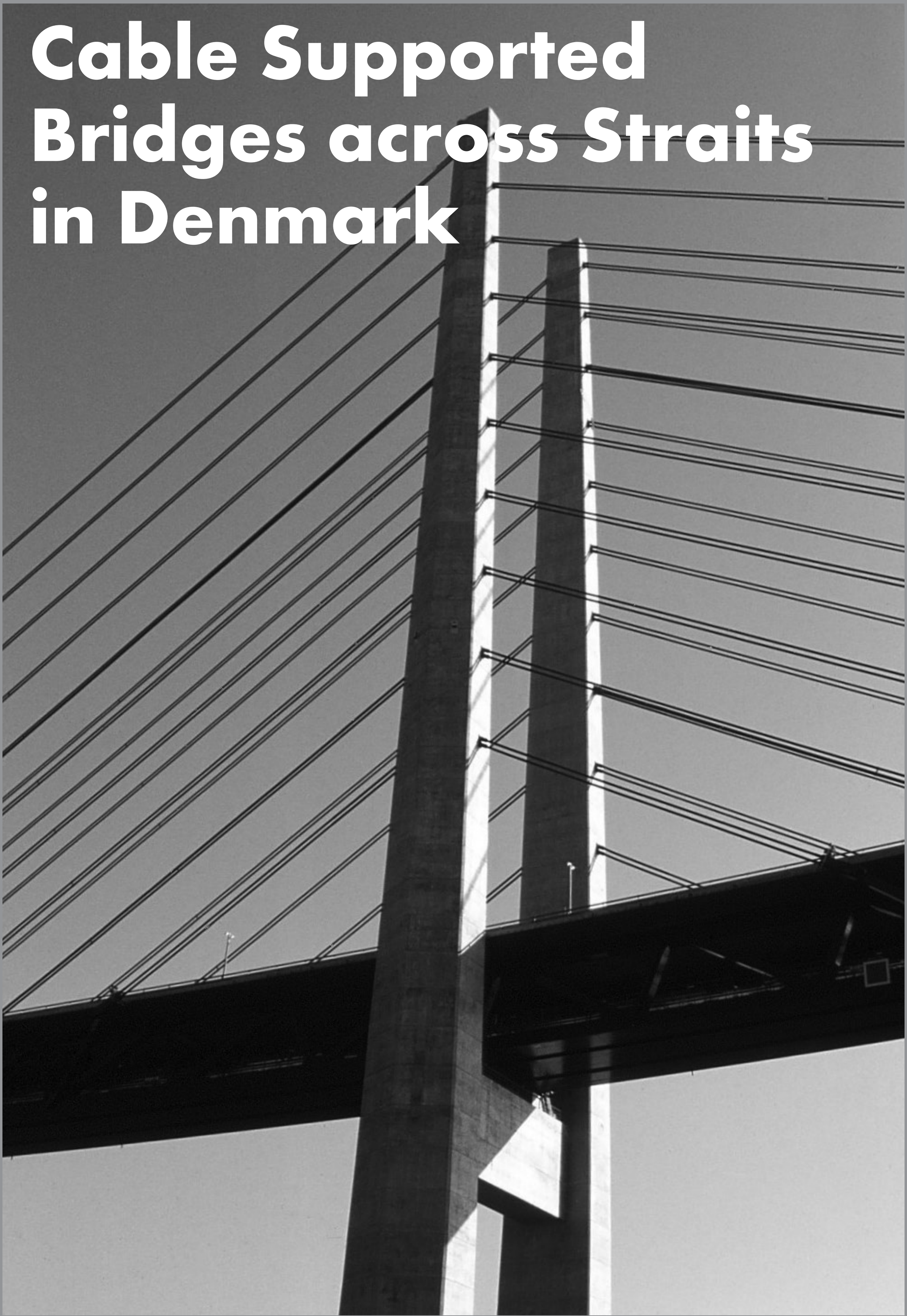
Cable Supported Bridges across Straits in Denmark



THE *Jylland* (Jutland) peninsula and the approximately 278 islands that form Denmark have had bridge connections since the Middle Ages. The most notable bridges of the 20th century are the high level bridges such as the Lillebælt Bridge from 1935 and the Storstrøm Bridge from 1937. Cable supported bridges and cable-stayed bridges have been making up the most significant infrastructural aspects which cross the seaways of the Baltic Sea.

By Niels Jørgen Gimsing

Bridges in Denmark – Historical Development

DENMARK consists of the peninsula of *Jylland* (Jutland) extending north from Germany and 78 inhabited islands (plus more than 200 small uninhabited islands).The capital of the country, Copenhagen, is situated on the largest island, *Sjælland* (Zealand), [figure 1].

In the Middle Ages wooden bridges were built in large numbers across brooks of moderate widths but none of these bridges has survived to our time. Remains of a few medieval stone bridges have been located in *Jylland* and it has been determined that the technique in constructing the vaults was similar to that used when building the vast number of village churches in the 12th and 13th centuries.

Up till around 1770 the majority of road bridges were still built of wood but after that time natural stone was used to obtain more reliable and durable bridges forming a part of a national net of highways. The stone bridges which were all of moderate size were generally composed of rough-hewed stone beams and piers as illustrated by the Immervad Bridge from 1786 [figure 2].

Major bridges across the straits separating the island kingdom were not built until the 1930s.

The most notable bridges were the high level bridges: Lillebælt Bridge from 1935 [figure 3] and the Storstrøm Bridge from 1937 [figure 4]. With its length of 3.2 km the Storstrøm Bridge was at completion the longest bridge in Europe, and it remained the longest road and rail bridge for a period of 60 years until it was surpassed by the West Bridge of the *Storebælt* (Great Belt) Link in Denmark.

For the Lillebælt Bridge the early designs from the beginning of the 20th century included suspension bridges as well as cantilever truss bridges. When the detailed design started in the 1920s only truss bridges were considered.

The bridges from the 1930s and early 1940s were generally built with a steel superstructure in the form of riveted plate girders, trusses or arches. In a few bridges the approach spans were made as concrete arches e.g. in the Queen Alexandrine Bridge [figure 5].

After World War II and the subsequent post-war period characterized by lack of resources the bridge building program was gradually revived in 1952, but initially only bridges of relatively modest size were actually constructed.

From 1970 to the mid 1980s a number of major bridges were built across straits as part of the new domestic motorway network. Some of these bridges were actually built as parallel bridges across the straits where bridges with narrow roadways of only 5.6 m width had been built in the 1930s.

Second Lillebælt Bridge

The second Lillebælt Bridge was opened to traffic in 1970 as the first major suspension bridge in Denmark [figure 10]. It gave a much needed improvement of the traffic capacity that had hitherto been offered by the narrow dual lane roadway on the first bridge from 1935.

The second Lillebælt Bridge was initially designed with a stiffening truss in accordance with the American tradition, but after the streamlined box girder design had been introduced for the Severn Bridge in the UK it was decided to use a similar concept for the Danish suspension bridge. So the Second Lillebælt Bridge became the second suspension bridge in the world to have a deck formed as a streamlined box in steel [figure 8].

The first bridge was built close to the location where the width of the strait is minimum, but the desire to have a more smooth alignment of the motorway resulted in a location of the new bridge where the Little Belt is about 50% wider. To also improve navigational conditions it was decided to build the new bridge with a main span of 600 m almost three times the main span of 220 m in the 1935 truss bridge.

At the time when the second Lillebælt Bridge reached the detailed design phase it was only realistic to consider a suspension bridge for a span of 600 m. Cable stayed bridges had at that time only been built with a span of up to about 300 m so it would have been a major step to go to twice that span. However, with the bridge technology of today it is very likely that the second Lillebælt Bridge would have been built as a cable strayed bridge.

The Second Little Belt Bridge also became the second major suspension bridge (span > 500 m) in the world with pylons made of concrete [figure 6].

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Figure 1. Strait crossing bridges built in Denmark up till World War II.

Figure 2. Immervad Bridge in Jutland.

Figure 3. The Little Belt Bridge from 1935.

Figure 4. Storstrøm Bridge, 1937.

Figure 5. The Queen Alexandrine Bridge, 1943.

Figure 6. The Second Little Belt Suspension Bridge, 1970.

Figure 7. The Second Little Belt Suspension Bridge with the underground anchor block.

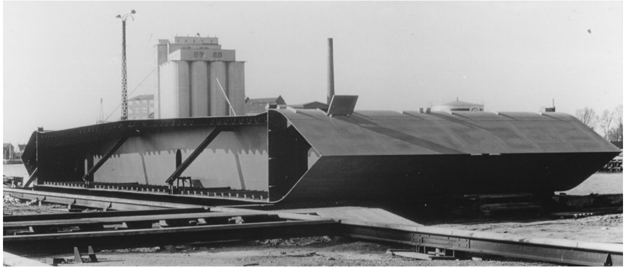
Figure 8. The Second Little Belt Suspension Bridge, a streamlined box in steel.

Figure 9. Second Little Belt Suspension Bridge splay chamber.

Figure 10. Second Little Belt Suspension Bridge.

Figure 11. The Farø Bridge (southern crossing).

Figure 12. Design from 1936 for a Great Belt Bridge.



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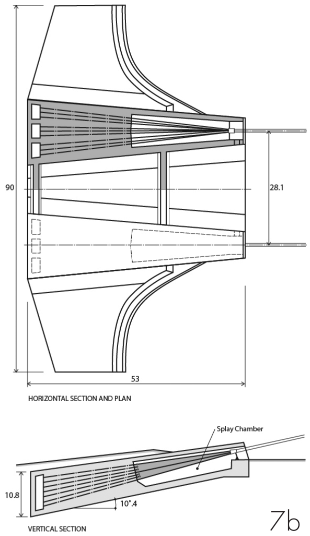
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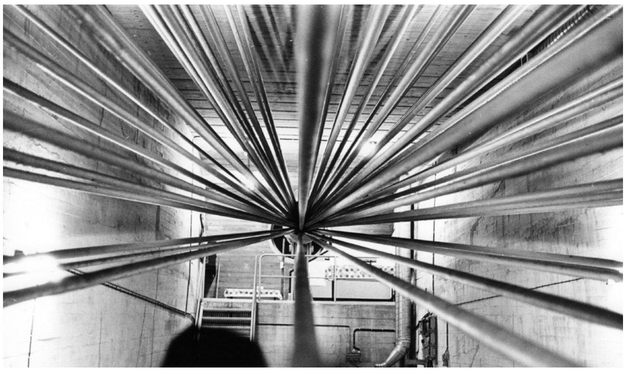

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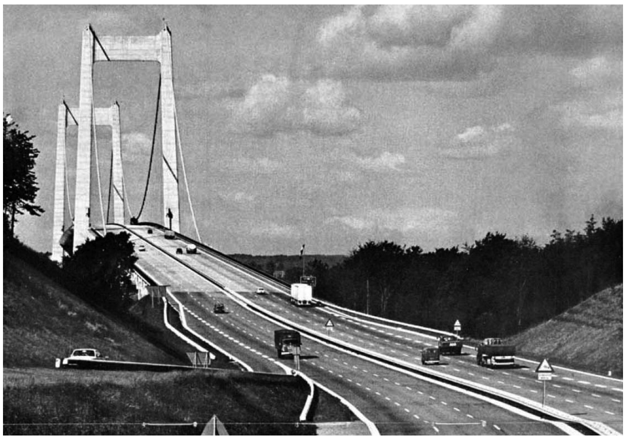

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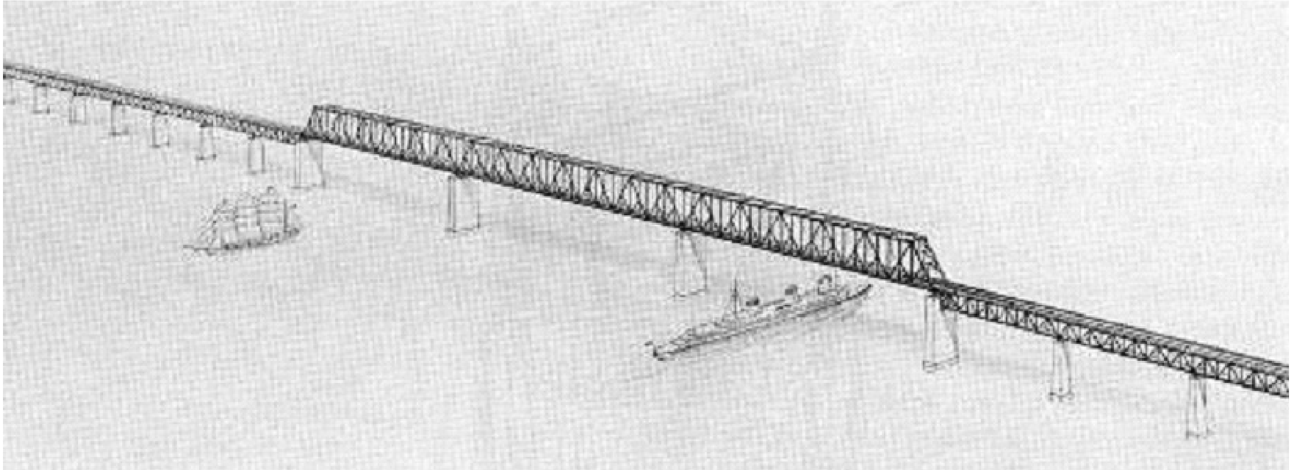

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Since the late 1960s steel bridges in Denmark have been constructed with all joints welded both in the factory and on site. This is in contrast to many other countries where field joints more commonly have been bolted. By the use of welded joints it is possible to get an airtight interior of steel box girders and this was for the Lillebælt Suspension Bridge used to achieve a very efficient corrosion protection of all interior steel surfaces. By adding a dehumidification plant inside the steel box it was possible to keep the relative air humidity below 40% and at that relative humidity no corrosion will form on the steel surfaces.

The principle of dehumidifying the air inside box girders was developed by the engineers C. Ostenfeld & W. Jønsson (later renamed COWIconsult) during the design of the Lillebælt Suspension Bridge where the system has now been successfully in operation for more than 40 years.

Today dehumidification is applied all over the world as an efficient tool to protect interior steel surfaces against corrosion. Also a large number of box girder bridges originally built without dehumidification have later been retrofitted to improve the corrosion protection and avoid the complicated process of interior maintenance of steel surfaces.

A special problem facing the designers of the Lillebælt Suspension Bridge had relation to the design of the anchor blocks as they had to be founded on glacial tills with a relatively small shear strength. As huge and dominating anchor blocks were undesirable above the ground for aesthetical reasons it was chosen to construct underground anchor blocks [figure 7]. This anchor block is almost entirely buried below the surface, and by sloping the underside of the block approximately 10° it was possible to achieve that the resulting force between concrete and soil acted almost perpendicular to the interface.

The anchor block is shaped like a snow plough, and it consists of a continuous bottom slab, 1.5 m thick, with 2 anchor housings on top. Outside these housings the bottom slab is provided with a 4-metre-high front edge that can develop a considerable passive earth pressure in case the anchor block should start to slide. However, the calculated safety against sliding is about 2 even in the worst case.

Inside the anchor housings the strands of the cable are flared in the splay chamber [figure 9] and connected through sockets to threaded rods. As it is generally difficult to establish an efficient corrosion protection of the individual strands near the splay collar, a dehumidification of the entire splay chamber was used for the very first time in the anchor blocks of the Little Belt Bridge.

Farø Bridges

As a supplement to the Storstrøm Bridge from 1937 the two consecutive Farø Bridges were completed in 1985 to carry a four lane motorway across from Sjælland to Falster. The tender design prepared by the owner, the Danish Road Directorate, called for a bridge with a continuous, multi-span concrete box girder in the northern Sjælland-Farø bridge and in the approach spans of the southern Farø-Falster Bridge where the main span was designed as a cable-stayed bridge. However, the successful contractor had based his bid on an alternative design with a superstructure in steel [figure 11]. That proved to be a competitive solution mainly because the 80 m full span box girder units could be fabricated at a shipyard and erected in one piece.

The two Farø Bridges comprise a 1,696 m long northern bridge between Zealand and the small island of Farø and a 1,726 m long southern bridge between Farø and Falster. Both bridges have a continuous superstructure from abutment to abutment, i.e. with no expansion joints inside the steel superstructure but only at the transition to the abutment. Most of the spans are 80 m long but across the navigation channel between Farø and Falster a cable stayed bridge with a 290 m long main span is found.

The deck of the cable stayed bridge is supported by a central fan-shaped cable system supported onto a diamond shaped pylon in concrete. The pylon shape was chosen to avoid the additional width of the central motorway reserve required if a vertical pylon in the cable plane should have been used, and to limit the width of the caisson below the water surface. The configuration of the Farø Bridge pylon actually marks the first application of a genuine diamond shape that has subsequently been widely used all over the world.

The 290m long main span is flanked on either side by 100 m long side spans. As the fans are of equal length in the main span and side span the anchor piers are not positioned at the end of the side span fans but at the deck anchorage of the second stay cable from the top. This activates efficiently the three stays at the end of the side span fan as backstays so a heavy single backstay is avoided.

The interior of the Farø Bridge deck is also corrosion protected by dehumidification—a feature that for this bridge proved to be decisive for the choice of a superstructure in steel rather than in concrete.

Storebælt Bridge

With the bridges built in the 1930s the main parts of Denmark were linked together in two units, one comprised of the *Jylland* peninsula and the second largest island, *Fyn* (Funen) and the other of the main island, *Sjælland,* and the islands to the south. So, one bridge was missing to link the entire country together: a bridge across the *Storebælt* (Great Belt) between *Sjælland* and *Fyn*.

To build that bridge was a task of quite a different magnitude than the other bridges of the 1930s as the width of *Storebælt* from coast to coast is 18 km—almost six times the length of the Storstrøm Bridge from 1937. Furthermore, a Storebælt Bridge would cross the international navigation channel from the Baltic Sea to the North Sea so it had to be built to allow passage of the largest ocean-going vessels.

The first realistic plans to construct a Storebælt Bridge were presented in the late 1930s [figure 12], and preparatory works such as soil investigations were planned to start in 1940 but the outbreak of World War II made it impossible to proceed with the project at that time.

It was not until 1987 that the Danish Parliament took the final decision to start the construction of a fixed traffic link across Storebælt. Due to the location of a small island, Sprogø, in the middle of Storebælt the link was to be composed of two bridges and a tunnel.

Across the Eastern Channel with the international navigation channel the link consists of a high level motorway bridge and a bored railway tunnel whereas the Western Channel is crossed by a low level bridge carrying both road and rail traffic.

The most impressive part of the Storebælt Link is undoubtedly the 6.8 km long East Bridge with a main span designed as a suspension bridge. That span was at the completion in June 1998 the second longest span in the world—surpassed only by the span of the Akashi Kaikyo Bridge in Japan.

The suspension bridge has a length of 2,694 m between the anchor blocks: a main span of 1,624 m flanked by two side spans each measuring 535 m.

The steel box girder forming the deck of the suspension bridge is 4.34 m deep and 31.0 m wide.

The box girder is supported vertically at the anchor blocks and by the vertical hangers from the main cables. At the pylons the deck is only supported in the lateral direction but free to move vertically. At midspan the main cables are fixed to the box girder through a long central clamp. Together with installation of large hydraulic buffers between the box girder and the anchor blocks the central clamp improves the stiffness under short term, asymmetric load and increases the frequency of asymmetric vibration modes. In case of long term movements, e.g. from temperature change the longitudinal buffers do not give resistance.

As the box girder is continuous over the full length of 2,694 m and no vertical support was needed then it became unnecessary to add a cross beam between the two pylon legs immediately below the deck. The omission of the cross beam below the deck also clearly illustrates the fact that the deck of a suspension bridge is supported by the cable system and do not carry the global load by bending to the pylons. Without a cross beam at deck level it was possible to position the lower deck beam at midheight of the 254 metre high pylons [figure 13].

During the conceptual design of the East Bridge emphasis was laid on arriving at a clean and pleasing appearance as seen in the configuration of the pylons. But also the anchor blocks were treated aesthetically to arrive at a more elegant form than found in many of the existing massive looking anchor blocks. With its location at mid sea it was attempted to give the East Bridge anchor blocks a more transparent look [figure 14].

Figure 14. The East Bridge anchor block.

Figure 13. The 254 meter high concrete pylon of the East Bridge.

Øresund Bridge

Overlapping with the construction of the Storebælt Bridges was the construction of the Øresund Bridge between Denmark and Sweden. Here the superstructure is designed as a double deck truss with two railway tracks on the lower deck and a four lane motorway on the upper deck [figure 15]. The total length of the bridge is 7.8 km which made it the longest bridge in the world for both road and rail traffic at the time. At completion in 2000 the main span of 490 m was also the longest in the world for a cable-stayed bridge carrying both road and rail traffic.

Across the navigation channel the Øresund Bridge comprises a cable stayed bridge with a total continuous length from expansion joint to expansion joint of 1,102 m. The continuous truss is supported by harp-shaped cable systems except for the outer regions close to the expansion joints. The anchor piers closest to the pylons render vertical support inside the side span harps and that has a pronounced influence on the stiffness of the system.

The main span deck consists of a transversally prestressed concrete slab acting compositely with the top chords of two vertical steel trusses. The lower railway floor is made entirely in steel in the form of a shallow multi-cell box [figure 16].

All truss members are box shaped with interior dehumidification.

Due to the design of the pylons as free-standing posts above the roadway the cable planes have to be vertical and positioned in some distance from the edges of the roadway slab. To transfer the load from the main trusses to the cable anchorages triangular brackets or "outriggers" are added outside the trusses. To make it possible to connect the outriggers efficiently to the main trusses the geometry of the diagonal bracing is changed from the approach span where all diagonals are of the same length to a system with long diagonals in the direction of the stay cables and short diagonals in between so that the node distance is kept constant [figure 17].

With the overall design leading to vertical cable planes outside the deck it was possible to let the pylons consist of vertical free-standing posts above the deck. By ensuring that the centroid of the pylon is positioned in the vertical cable planes the cross section of the pylon is subjected to pure uniform compression from dead load and vertical traffic load acting on the deck.

Innovative design features of the Danish Cable Supported Bridges

As it has been described above the cable supported bridges built in Denmark have in several cases introduced new design features, as it is outlined below:

- Continuous superstructures without change of deck shape from approach to main spans (Farø and Øresund Bridges)
- Intermediate pier support in the side span fans/harps (Farø and Øresund Bridges)
- Dehumidification of the interior in steel box girders (Lillebælt, Farø, Storebælt and Øresund Bridges)

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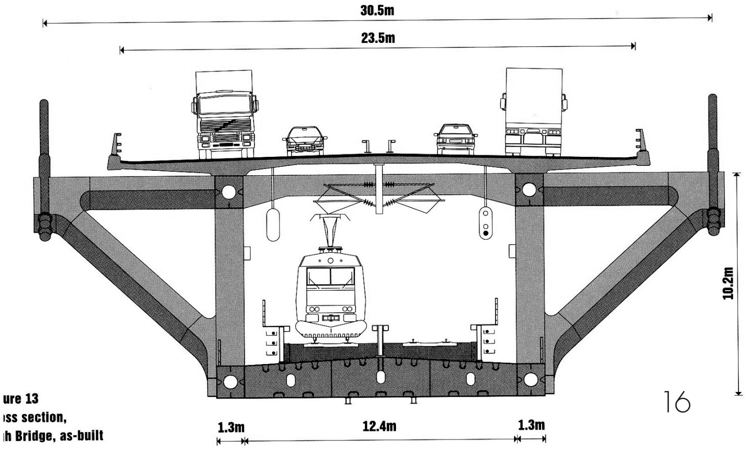

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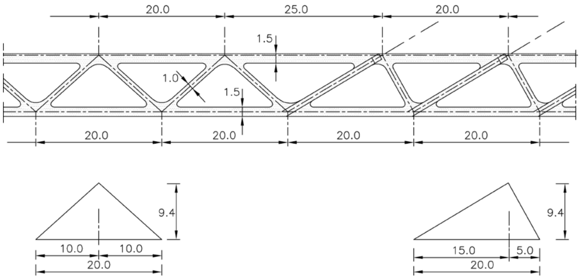

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Figure 15. The Øresund main bridge.

Figure 16. Cross section of the main span in the Øresund Bridge.

Figure 17. Change of truss geometry from approach bridge to cable stayed bridge.

- Dehumidification of the interior in main cable saddles (Storebælt Bridge)
- Dehumidification of the interior in splay chambers (Lillebælt and Storebælt Bridges)
- Concrete pylons (Lillebælt, Farø, Storebælt and Øresund Bridges)
- Diamond shaped pylons (Farø Bridge)
- Portal shaped pylons without a cross beam below the deck and only two above (Storebælt Bridge)
- Free-standing concrete pylon legs above the bridge deck (Øresund Bridge)
- Anchor blocks with reduced visual impact (Lillebælt and Storebælt Bridges).

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