The Danish Bridge Heritage

Lars HAUGE
Chief Project Manager
COWI A/S
Lyngby, Denmark

Lars Hauge, born 1962, graduated from the Technical University of Denmark in 1986. Since 1990 he has been employed by COWI A/S in Copenhagen in the department for major bridges, and have been involved in the design of some of the worlds largest bridges.

Summary

The recent activities within infrastructure projects in and around Denmark are unprecedented. The 18 km Great Belt fixed link was completed in 1998, investigations have been carried out for a 19 km fixed link across the Fehmarn Belt between Denmark and Germany, and the 16 km Øresund fixed link between Denmark and Sweden was inaugurated in year 2000.

The Little Belt Bridge (inaugurated in 1970) and the Faroe Bridges (inaugurated in 1983), were the first cable supported bridges to be designed and constructed in Denmark. They were innovative at the time of construction and the experience gained from these projects in design, tendering and construction have been important for the development of three major Scandinavian Links.

The design and construction of the major Scandinavian Link has contributed to the development of bridge design and construction and features from these projects have subsequently been implemented on projects all over the world.

The paper gives a brief introduction to the projects and describes some of key features of the projects.

Figure 1 The Scandinavian Links

1. Background

1.1 The Little Belt Bridge

The design development of the Little Belt Bridge suspension bridge was inspired by the contemporary suspension bridges, the Tancerville bridge in France, the Severn bridge in England and 2nd Forth Road bridge in Scotland. The bridge was designed with concrete towers like the Tancerville bridge in France and with a closed steel box girder like the Severn Bridge. The main cable is composed of prefabricated strands, the selection being made based on competitive tendering of both a spun cable and a prefabricated cable. The main span is 600m. The bridge was the first bridge to utilize dehumidification to protect the interior of the box girders against corrosion.

Figure 2 The Little Belt Bridge

1.2 The Faroe Bridges

The Faroe Bridges are composed of two bridges, a viaduct bridge and a cable stayed bridge with approaches. The bridge deck is designed as a closed steel box girder throughout the length of the bridge with long joint free expansion sections. The tower is in concrete with a steel structure for the stay cable anchorages. The stay cables are arranged in a central line and the torsional support of the bridge girder is composed of hydraulic pistons at the towers. The superstructure of the approach bridges were erected as full span sections of 80m's length.

2. The Scandinavian Links

During the 80ties and 90ties the Great Belt Link and Øresund Link were constructed in Scandinavia and the feasibility of the Fehmarn Belt Link was thoroughly investigated.

2.1 The Great Belt Link

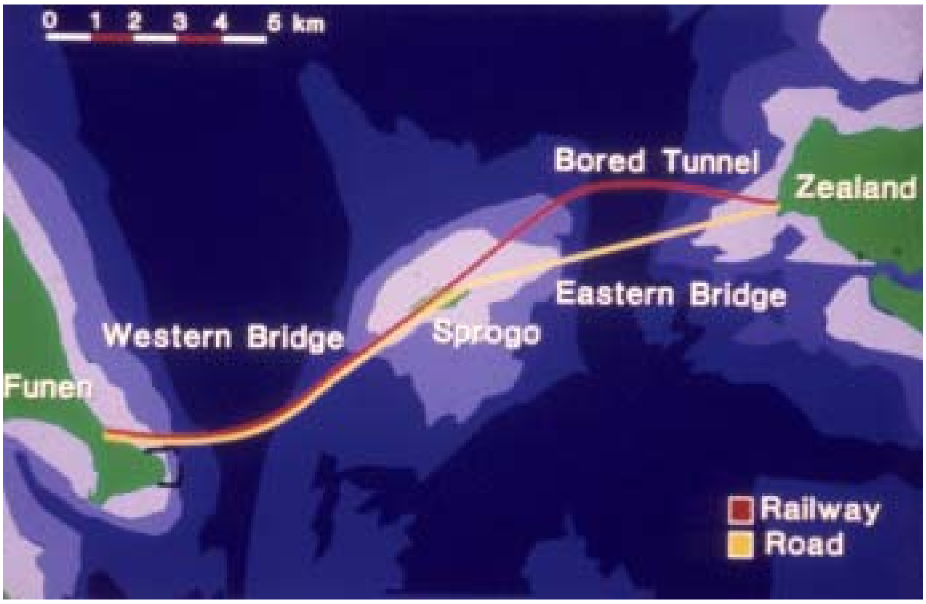

Figure 4 The Great Belt Link

The Great Belt Link connects the eastern and western part of Denmark. The Great Belt is divided into two channels, east and west, by the small island, Sprogø, which has been an obvious stepping stone for the projects. The project comprise three elements, a low level bridge for combined road and railway traffic (the West Bridge), a bored tunnel for railway traffic (the East Tunnel) and a high level bridge for roadway traffic (the East Bridge).

The 6.6 km West Bridge is composed of two haunched concrete box girders, one for roadway traffic and one for dual track railway traffic, with a typical span length of 110.4 m, reduced to 81.75 m at the abutments and the expansion joints. The East Bridge consists of a 1624 m main span suspension bridge with two approach bridges, 2,530 m and 1,538 m, respectively. The span length of the approach bridges is 193 m. The East Tunnel, a bored tunnel, consists of two 7.7 m internal diameter tubes, each 7,412 m long and 25 m apart. At the deepest point, the rails are 75 m below the sea level.

2.2 The Øresund Link

The 16 km fixed link for combined railway and highway traffic between Denmark and Sweden consists of three major projects; a 3.7 km immersed tunnel, a 7.8 km bridge and an artificial island which connects the tunnel and the bridge.

The 7.8 km bridge includes a 1,090 m cable stayed bridge, the high bridge, with a main span of 490 m. The 3,013 m and 3,739 m approach bridges have spans of 140 m. The entire superstructure is a composite structure with steel truss girders between the four-lane highway on the upper concrete deck and the dual track railway on the lower deck.

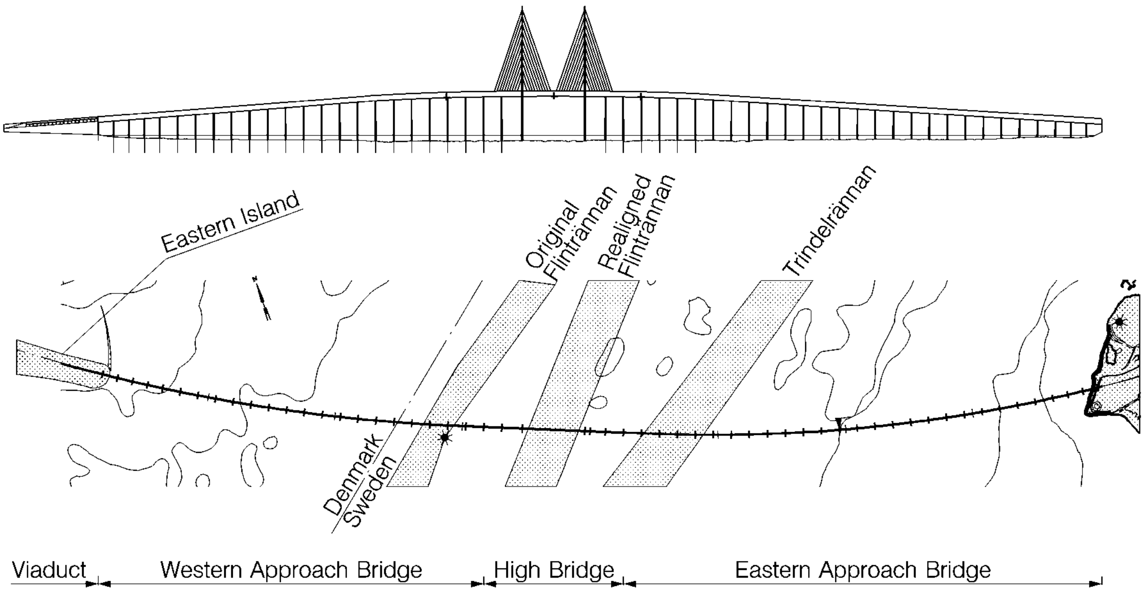

Figure 5 The Öresund Bridges

2.3 The Fehmarn Belt Link

In 1995 the Danish and German Ministry of Transport invited eight consulting consortia to tender for the preliminary investigations for a fixed link across the 19 km wide Fehmarn Belt. The results of the study constitutes the basis for public discussions and political decisions whether to establish a fixed link, and also which concepts should be preferred.

A variety of concepts have been investigated, comprising bored and immersed tunnels for trains and shuttles, bored and immersed tunnels for combined road and railway traffic and bridge solutions.

The technical feasibility study was completed in early 1999.

3. Integrated Approach

For any major infrastructure project it is important that wide range of aspects are considered in the early phases in order to arrive at an overall optimised solution that consider technical, environmental, financial, traffic, aesthetic and risk aspects. The integrated approach - especially the influence of risk and environmental impact on the technical solutions has been important for the three major Scandinavian links, because they crosses main navigation routes to the Baltic sea and because of the sensitive marine environment in the Baltic sea.

3.1 Feasibility Studies

The Technical Feasibility Study for Fehmarn Belt Link should clarify all technical aspects of the fixed link including aesthetic, environmental and risk aspects. Six solutions comprising bridges, bored tunnels and immersed tunnels were developed in close co-operation with architects and were evaluated and compared in terms of risk, traffic and environmental impact.

The bridge solutions comprise either a triple 724 m main span cable stayed bridge or a 1752 m main span suspension bridge both for combined motorway and dual track railway traffic arranged in two levels. The size of the main span was determined to give acceptable navigational conditions in the international shipping route connecting the Baltic sea with the North Sea.

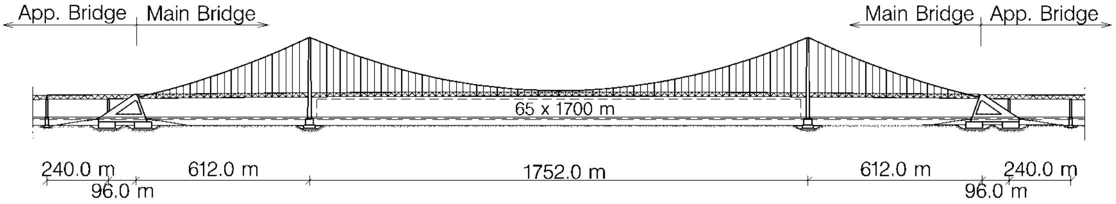

Figure 6 Suspension Bridge Option

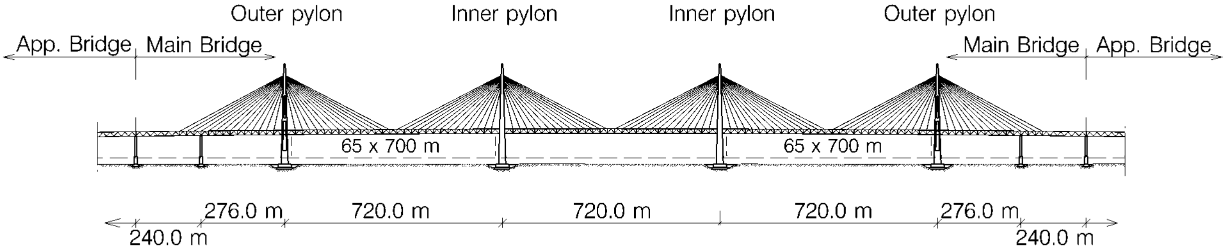

Figure 7 Cable-Stayed Bridge Option

The concrete pylons will be 285 m and 281 m high for the suspension and the cable stayed bridge, respectively. The anchor blocks for the suspension bridge will be protected by hydrodynamically shaped artificial islands, whereas the back span piers for the cable stayed bridge will be designed as fail-safe for ship impact, i. e. limited operation can be maintained without a back span pier.

The approach bridges, carrying the traffic to the main bridges, are steel/concrete composite structures composed of a steel truss with a concrete deck on top. The railway will run inside the steel truss on a lower steel deck while the roadway traffic will run on the upper concrete deck.

The span length in the approach bridges is 240 m long, partly to reduce the water blocking effect and the ship collision risk and to increase the ship impact capacity. The applicability of the long spans is further substantiated by relative large water depth, approximately 20 m to 30 m over almost the entire width of the belt.

The approach bridges are founded on cellular caissons, which are imbedded in the seabed to minimise the blocking effect.

The impact on the environment was studied in detail in parallel with the design development of the concepts and the results have been integrated in the design as requirements to the design. Examples of environmental design requirements are:

- Streamlined protection islands
- Submerged bridge foundations
- Increased span length in the approach bridges
- Elliptical shape on the shafts of the approach span piers

The results of the environment studies are used in the comparison between the different solutions models. On a scale from 1 to 10, the cable stayed solution scored 2.5 and the suspension bridge solution 3.2. In the financial comparison between the concepts, construction and operational risk were quantified and included.

Similar considerations were made for the Great Belt Link and the Øresund Link, where the requirements to flow resistance to a large extent dictated the shape and size of the reclaimed land and the design of the foundations.

4. Innovations

It could be stated that today's innovations are tomorrows state-of-the-art. Innovations are therefore important to assure a continuous development in bridge design and construction.

4.1 Long span bridge design

Design of long span bridges has become a Scandinavian trademark and Danish bridge design and construction expertise are in demand all over the world. The Storebaelt, East Bridge is the second longest spanning suspension bridge in the world, and the Normandy Bridge was, when inaugurated, the longest spanning cable stayed bridge in the world with a main span 856 m. The Höga Kusten Bridge, in the northern part of Sweden, is with a main span of 1210 m among the 10 longest spanning suspension bridges in the world. The design of these bridges has provided an exceptional experience base which for instance has been utilised in the technical feasibility study for a fixed link across the Strait of Gibraltar, where multiple suspension spans of 3500 m as been proposed. COWI is involved in the design of the Stonecutters Bridge in Hong Kong (main span 1018 m) as sub-consultant to Arup, Hong Kong, in the Sutong Bridge in China (main span 1088 m) as the independent checker for the Jiangsu Provincial Government and on the bridge across the Canal de Chacao in Chile. The design of long span cable supported bridges requires extensive knowledge on the wind climate and on the structures response to the wind effects. This requires extensive testing that includes measurements of turbulence and coherence at the bridge site, section model testing, full bridge model testing and often also stay cable wind tunnel testing. If the bridge is located in seismic highly active areas site specific hazard analysis should be carried out and the effect analysed thoroughly.

Figure 8 Pont de Normandie

4.2 Multi tower cable supported bridges

Following a study of a wide range of solutions for Canal de Chacao, the concept, which was been adopted for the final tender design, comprises a northern suspended structure between Roca Remolinos (a submerged island in the middle of the strait) and the continental coast, and a somewhat smaller southern part connecting Roca Remolinos with the Chiloé Island. The cables are continuous from the north anchor block to the south anchor block. Due to the two spans, the central pylon can not be a normal vertical pylon, as this will lead to a very flexible structure. Thus, the central pylon shall provide a horizontal rigidity to the main cable passing over it, hence, the stiff A-framed pylon structure is a logical solution.

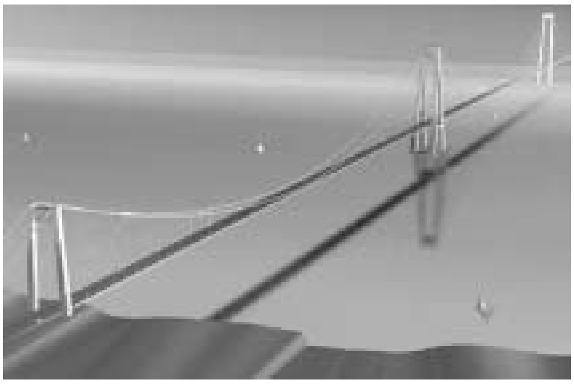

Figure 9 Canal de Chacao

A major advantage compared to the solution with two consecutive suspension bridges is, that the longitudinal spacing of pylon foundations on Roca Remolinos is reduced from 110m to only 50m. Considering the narrow plateau this means, that water depths will be limited at the foundation points, and that these will be located further away from steep slopes.

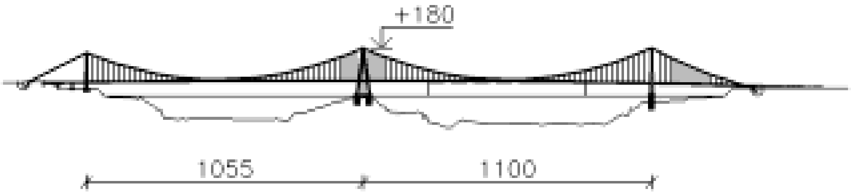

Figure 10 Continuous two-main-span suspension bridge

Traffic load in one main span will results in unbalanced loading of the central pylon.]. The pylon as such might be able to resist significant differential loads, however, the possible friction between the main cable and the saddle will set a limitation the maximum differential loads that can be transferred. It is therefore envisaged, that a clamp, which will increase the differential load capacity, shall be mounted on top of the central pylon saddle.

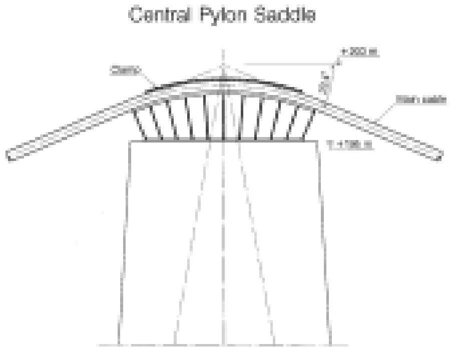

Figure 12 Central pylon saddle

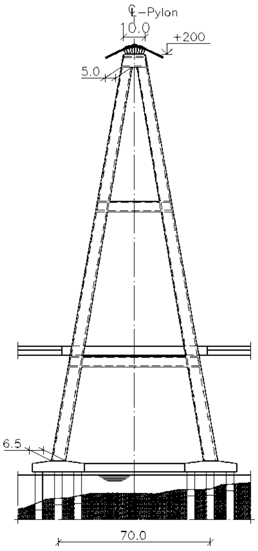

Figure 11 Roca Remolinos Pylon

The location and the construction of the bridge across the Canal de Chacao in a highly seismic region with large seismic design loads is one of the major critical issues for the entire project. Although large span suspension bridges are known to possess superior seismic capabilities, the design will be greatly influenced by the seismic demand. The tall pylons for the Chacao Bridge will be made of concrete.

It is well known that large span suspension bridges have an ample displacement capacity for seismic response. Fundamental periods of the vibration are long, and the peak displacement response of the bridge deck is likely to be similar to the peak ground displacement. In recent large earthquakes as in Kobe 1995 suspension and cable stayed bridges were subjected to strong ground motion. In general these flexible structures fared very well. The project will focus on the ability of the structure to survive under a very severe seismic action. According to the Design Basis and to the modern approach to seismic design, performance is defined in terms of two criteria: the functionality of the bridge and the resistance and related level of damage.

4.3 Articulation

In the very early phases of the design process a number of important decisions are made with regard to the articulation of the bridge. A wrong decision here will follow the bridge throughout its lifetime. During the Outline Design phase of the Great Belt suspension Bridge comprehensive studies were performed to determine the optimum ratio between the cable sag (f) to span length (L). If for example the ration f/L was decreased the following diverting effects would be:

- The main cable forces would increase and the amount of cable steel would consequently increase leading to increased costs.
- The required height of the pylons would decrease leading to reduced costs.
- The cable reactions on the anchor blocks would increase, and as a consequence the anchor blocks had to be increased which would lead to increased costs.
- The global stiffness of the bridge would increase, leading to reduced bearing and expansion joint movements and consequently to reduced construction and maintenance costs.
- The critical flutter wind speed would be reduced leading to increased construction costs.

A complete analysis of all effects is very complex. However, the tendency was clear that increased cable sag to span length ratio would lead to reduced construction costs. It was finally decided to base the detailed design on a cable sag to span length ratio of f/L=1/9.

From the very beginning one of the main objectives was to develop a bridge concept where the number of bearings and expansion joints was reduced to a minimum. Experience from other bridges had shown that maintenance works on these parts constitute a major part of the maintenance cost. Therefore a concept with a continuous girder over the full cable supported length of 2694 m was compared to the classical suspension bridge concept with expansion joints at the pylons. In the table below the horizontal deflections from traffic load are shown for the two systems based on different cable sags.

Static Main System	Ratio f/L	Horizontal movement (mm)	Vertical Deflection (mm)
Classical System	1/9	2400	8742
Continuous System	1/9	1820	8570
Classical System	1/11	1580	8000
Continuous System	1/11	1220	7820

Figure 13 Effect of articulation

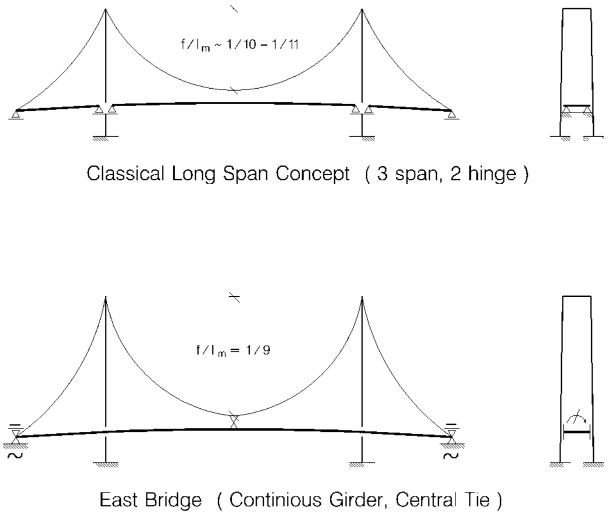

Figure 14 Statical Systems

The hardest problem to overcome with the continuous girder trough the pylons was the handling of the forced bending moments at the pylons caused by angular rotation of the main cables over the cable saddles. The girder deflection would more or less follow the cable deflection, and bending moments would be introduced. To minimise the forced moments in combination with dead and live load actions the supporting conditions were optimised based on a parametric study of hanger distances, hanger types (locked coil versus parallel wire strands), regulation of hanger forces, girder stiffness, supporting of the girder for vertical forces at the pylons, etc. The final solution was:

- 56 m distance between the hangers at the pylons. The normal distance is 24 m.
- No support of the girder for vertical loads at the pylons.

The bridge has been prepared for a torsional support at the towers by means of cross coupled hydraulic pistons. A similar system has been in operation on the Faroe Bridges. The system can be installed if the bridge behaves different than expected.

As a supplement the longitudinal movements at the anchor blocks were limited to 1.0 m by means of hydraulic pistons in order to limit the angular deflection of the hangers and the requirements to the expansion joints. The system also acts against quick movements to reduce the wear in the expansion joints and the bearings.

A side effect of the continuous bridge girder concept was an aesthetically improved appearance enhancing the perception of the bridge being carried by the cables rather than by the pylons.

Cable Stayed Bridges

Similar considerations are carried out for cable-stayed bridges. The Normandy Bridge can be mentioned as an example. The articulation of the Normandy Bridge with the 116 m cantilever in concrete and monolithic joint between the girder and the pylon might seem a little unconventional. However, having studied the bridge in detail it is clear that these features are advantageous for the bridge. During construction the steel part of the girder acted as if it was supported not at the pylons, but 116 m out in the main span, and thus reducing the deflection.

The cable configuration layout of the tower is extremely important for a long span cable stayed bridge. An A-tower will in some cases increases the critical wind speed by 20% compared to a H-tower.

4.4 Computer Tools

As computer power increases more and more sophisticated calculations can be performed providing the bridge designers with useful information of the behaviour of the structures.

4.4.1 Wind Simulations

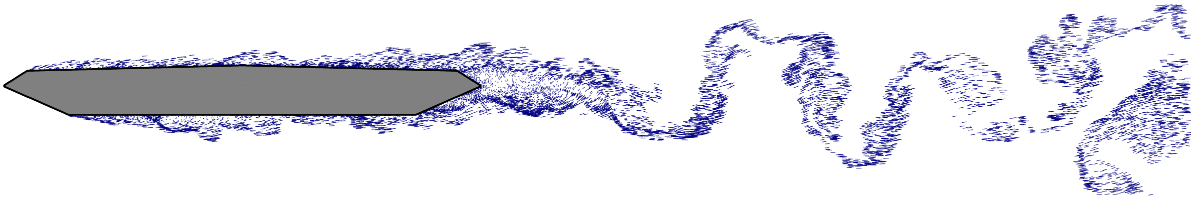

Figure 15 Visualisation of simulated flow around a bridge box girder section undergoing forced vertical bending motion

COWI has developed a computer tool, which can be used with great advantage for comparison of bridge girder concepts, DWMflow. Based on a description of the cross-section, DWMflow calculates static windload coefficients (drag-coefficients), flutter-coefficients and vortex shedding response. This means that a qualified evaluation of for instance, different cross sections could be carried out in a short time without recourse to physical wind tunnel tests. The "artificial" windtunnel has been compared with wind tunnel test results with good compliance.

4.4.2 Soil Structure Interaction Calculations

The pylons for the Öresund Link are founded directly on Copenhagen limestone. The foundation structures are cellular caissons with a footprint of 35 m x 37 m.

One of the key issues in the design has been to keep the dimensions and the weight of the caissons as low as possible because of the size of the available dry-dock facilities and the available draft during tow-out. Intensive co-operation between designers and contractors was established throughout the project to achieve these goals. The result lead to a design which to an outsider may look inefficient, as for instance the ribs, supporting the bottom slab. But a total optimisation considering design, fabrication and transport lead to the present design. The structure is post-tensioned in the bottom slab, in the ribs and wall and in the top slab.

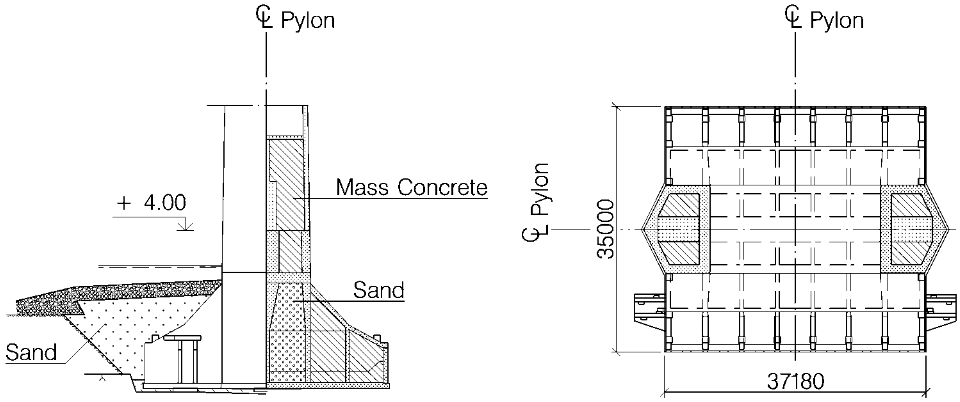

Figure 16 Pylon caisson

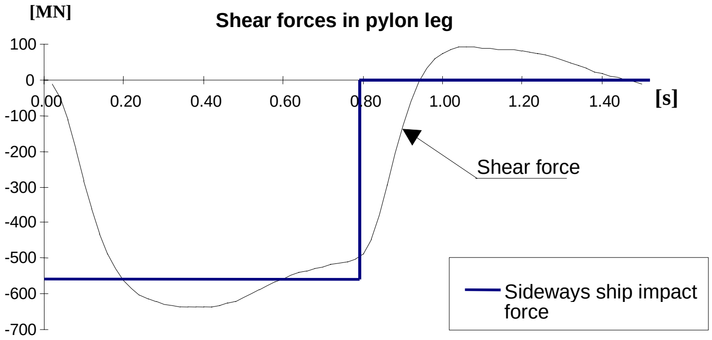

Figure 17 Dynamic shear force at level -17.0 m

The dominating load for the foundation is ship impact. The caisson is designed to withstand a ship collision force of 560 MN in the longitudinal direction and 438 MN in the transverse direction of the bridge excluding dynamic enhancement. Dynamic ship collision analyses were carried out on a computer model of the entire bridge to determine the dynamic enhancement and the amount of load being transferred trough the cable system to the other pylon. The calculation showed peak-forces of 638 MN and 651 MN for the east and the west pylon caisson, respectively.

Advanced soil/structure interaction calculations were carried out to demonstrate the bearing capacity and the requirements to plastic deflections after a ship collision. Prior to tender, the Client, had carried out extensive field and laboratory tests, including determination of stress strain curves for 1m x 2m plates which made it possible to determine a stress limit for the limestone.

This lead to the following verification procedure for ship collision:

The dynamic amplification of the impact force was determined, based on a linear elastic time history analysis of the ship collision on a 3D finite element model of the entire cable-stayed bridge with the foundations modelled as linear elastic springs.

For the verification of the soil/structure interface a non-linear material model, a Druger-Prager cap model, was calibrated, based on full-scale tests carried out by ÖSK.

The force-displacement curve for the foundation, subjected to the enhanced ship collision force, was determined using a non-linear model of the caisson and the surrounding soil.

The linear elastic time history analysis was re-done with the spring constant for the foundations, found in the force displacement analysis.

The bearing capacity of the foundation was verified.

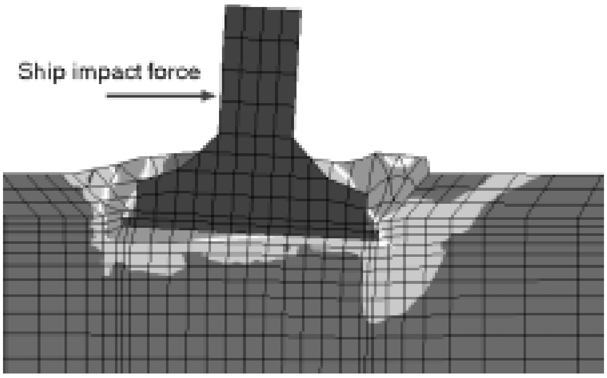

Figure 18 Plastic zone development

5. Service Life Design

The sixties and the following years have been characterised by an important economical growth mainly in the western countries, the result of which has lead to intensive investments in infrastructure projects, including thousands of major bridges. Efforts have mainly been concentrated on achieving low initial construction costs and minimise the construction period. Today, the effect has begun to show in the form of an increasing amount of damages on these bridges.

Therefore, long service life design concepts for 100 years or more are becoming a basic requirement for major projects. The result is a considerable impact on the development of bridge construction technology.

The trends to achieve more durable structures include:

5.1 Designs which favour continuities.

An example is long, continuous girders to limit the number of joints, which are susceptible to early deterioration. Expansion sections exceeding one km are now usual practice for both steel and concrete bridges. The largest continuous girder so far has been designed for the Storebælt East Bridge over the full cable supported girder length of 2694 m. Due to these very large expansion sections, it has now become common practice to install hydraulic buffers which can limit the longitudinal movements from live loads, but at the same time allow slow movements from temperature variations.

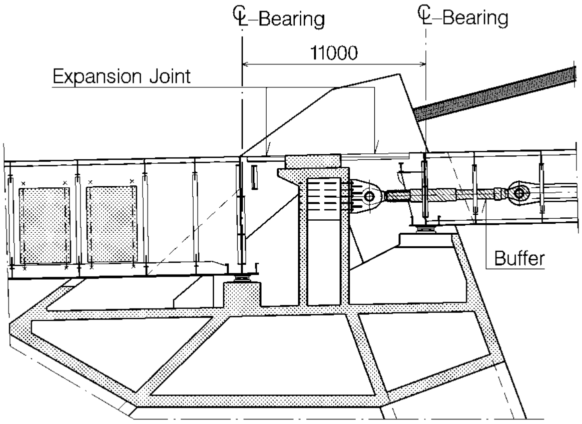

Figure 19 Arrangement at Anchor Blocks

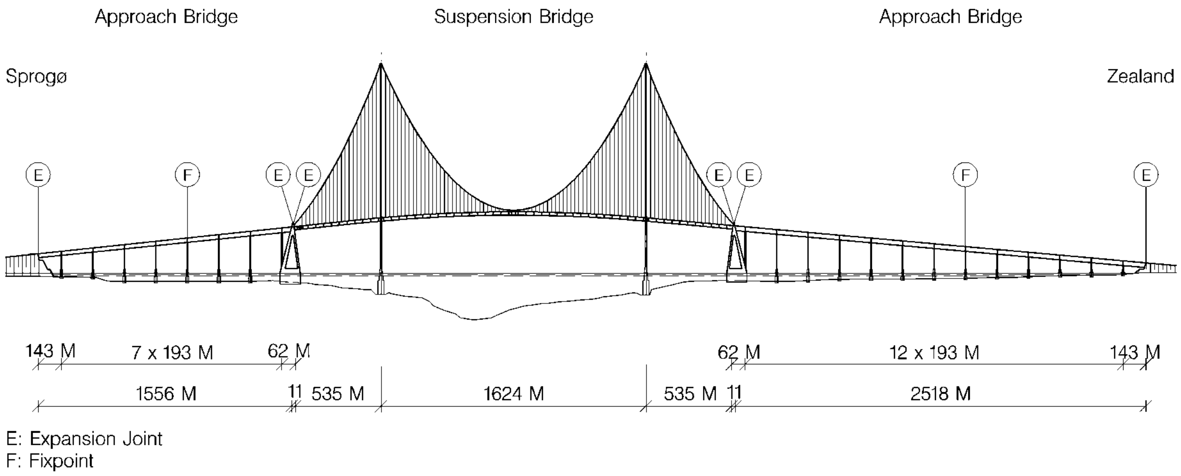

Figure 20 Structural layout of the Great Belt, East Bridge

5.2 Design with simple structural forms.

A complex geometry, many edges and large exposed surfaces are sensitive to deterioration. Therefore, simple structural forms with a minimum of exposure to the environment are to be preferred. An example is the closed steel box girder. The outer surface is completely smooth with a minimum of exposure and easy to maintain. The interior, which comprises about 80 percent of the total steel area with stiffening troughs and bulkheads, can be corrosion protected by dehumidification and thus does not need to be painted. The principle in dehumidification is to keep the relative humidity inside the box below 40 percent, leaving an adequate margin to 60 percent, the limit above which corrosion may take place. This can be achieved by installation of a simple fan system for circulation of the enclosed air and a dehumidifier unit equipped with hygroscopic filters.

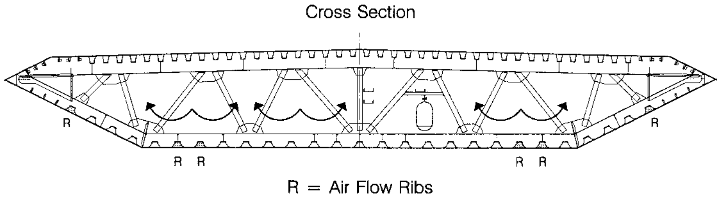

Figure 21 Dehumidification principle on a closed steel box girder, cross section

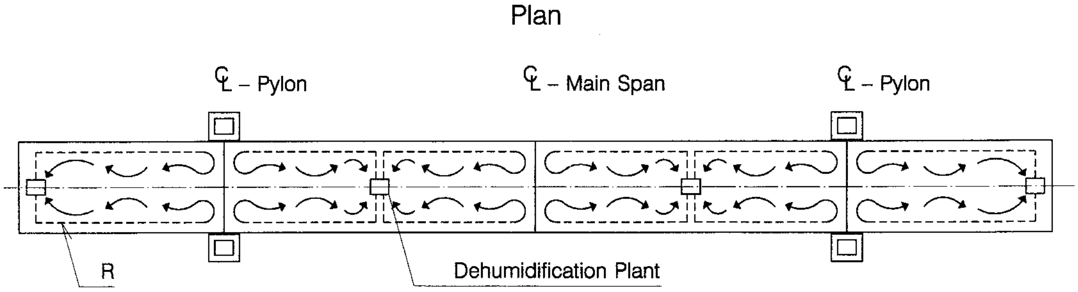

Figure 22 Dehumidification principle on a closed steel box girder, cross section, Plan

5.3 Design based on multi-stage protection strategy especially for concrete bridges.

The principle is that the designer introduces different protective measures which may act simultaneously or substitute each other once the former has been overcome. To prevent corrosion of reinforced steel and post-tensioned cables, the protective barriers may be tanking, membranes or coating as the first measure, followed by the concrete cover. The effectiveness of this barrier will depend of the cover thickness, the concrete composition, and the limitation of crack development. A third barrier may be an epoxy coating of the reinforcement or use of plastic sheating for post-tensioned cables. As an active protective measure, cathodic protection or sensor monitoring may be applied.

6. Fabrication and Erection

Fabrication and erection of the major bridge projects in Scandinavia is characterised by off-shore/off-site prefabrication, large transport distance and erection of large elements. This exemplified in the descriptions below.

6.1 The Storebaelt, West Bridge

Altogether 324 pre-fabricated units, comprising 62 caissons, 124 pier shafts and 138 bridge girders have been cast in a pre-fabrication yard close to the bridge site. The elements were cast in five production lines and moved on sliding surfaces by pushing units to the load-out jetties, where they were lifted off by a large purpose-built heavy lift crane vessel, The Swan, for further transportation and installation at the bridge site.

Figure 23 West Bridge, Prefabrication Yard

Caissons, weighing up to 7,400 tonnes, were placed by The Swan on 1.5 m thick crushed stone foundation beds which were compacted and screeded to tight tolerances by means of a

læll

Figure 24 Erection of the Great Belt, West Bridge

Foundation bed preparation by a multi-purpose jack-up rig for the Storebælt West Bridge. The pier shafts were connected to the caissons 3.5 m below the water line by casting the joint in the dry within a removable cofferdam on top of the caisson. Finally, the railway and the roadway girders, weighing up to 6,600 tonnes, were slowly lowered onto the bearings. Cantilevering from the pier, the gap between two consecutive girders was only 2 m, which was closed by in-situ concreting, the only cast-in-situ concrete on the entire superstructure.

6.2 The Storebaelt, East Bridge

Figure 25 The Great Belt, East Bridge

The 6.8 km East Bridge includes a suspension bridge with a main span of 1624 m and side spans of 535 m. The approach bridges have spans of 193 m. The design of the entire bridge superstructure is based on closed steel box sections, which consist of few basic elements; flat panels with trough stiffeners, transverse bulkhead beams and trusses. They are well suited for rationalised repetitive fabrication.

In Livorno, Italy, the panel production was carried out in an existing workshop, suitable for the purpose. In Portugal a major pre-assembly yard was established at the harbour of Sines for the panels to be assembled to girder sections, typically 40 m long for the approach bridges. They weighed about 500 tonnes when they were tugged on barges to Aalborg in Denmark, where they were joined together to full 193 m spans, before they were transported to the bridge site and erected on the piers. The 48 m erection sections for the suspension bridge were trial assembled and completed at the pre-assembly yard in Italy (Taranto) and Portugal (Sines).

6.3 The Øresund Fixed Link

Figure 27 Planning

Figure 26 Execution

Fabrication of the steel trusses for the Öresund Bridges as well as casting of the concrete deck is carried out in Spain. The complete 140 m long girder sections, weighing up to 7,000 tonnes, are tugged on flat barges to the bridge site and lifted into position on the piers by The Swan, the vessel used for the Storebælt West Bridge. In between the job on the two Danish bridges, The Swan has been used to erect the 13 km Prince Edward Island Bridge in Canada after being modified and having the lifting capacity increased to 8,700 metric tons.

The Swan has erected the entire bridge girders. On the cable-stayed bridge the girder will also be erected in 140 m sections on temporary supports before being suspended by the stays. This method is unusual for a cable-stayed bridge, but it is attractive due to the availability of the heavy lift vessel, and it reduces the construction time and limits ship traffic disturbance.

7. Conclusion

The construction of the fixed link in Scandinavia has developed modern design strategies and unique structures. The bridges represent state-of-the-art in terms of design, tendering and construction and will be best practices for the years to come.