CRITICAL ANALYSIS OF THE GREAT BELT EAST BRIDGE, DENMARK

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Abstract: This article provides an informative and critical analysis of The Great Belt East Bridge in Denmark. Not only is it one of the longest span bridges in the world but it was also part of the greatest engineering feat ever undertaken in Danish history. Its legacy is that the kingdom of Denmark is now fully linked up with mainland Europe, improving trade and transport. It paved the way for further bridging success between Denmark and Sweden with the Oresund Bridge. More than 10 years later, it is still regarded as one of the greatest bridges in the world as well as being a cultural and engineering icon for the people of Denmark.

Keywords: Great Belt, East Bridge, Suspension, Denmark, Vortex induced oscillations

1 Introduction

The Great Belt, or Storebaelt in Danish, is a 16-32km wide strait between two of the largest Danish islands, Zealand and Funen/Fyn. For hundreds of years the ferry route between the two islands was regarded by the Danes as extremely important, but ferry services were often disrupted due to storms and particularly harsh winter conditions.

A link to replace the ferries became the source of debate for a number of decades until 1987 when a fixed link was finally approved by the Danish government. Construction of the link commenced in 1988 and, although the link had been open to rail traffic for over a year, Queen Margethe II of Denmark finally declared the last part of the link the East Bridge open to road traffic on the 14th June 1998. It was declared as the largest engineering project in Denmark, shrinking the size of the country, linking the capital Copenhagen to the rest of Denmark as well as mainland Europe.

The fixed link itself is broken up by the island of Sprogo and consists of a suspension bridge and a railway tunnel between the islands of Sprogo and Zealand as well as a box girder bridge between the islands of Funen and Sprogo (see Fig. 2).
With Pylons reaching up to 254 metres the suspension bridge on the east side of the great belt is without a doubt the most visually impressive part of the whole project. The completed East Bridge has a central span of 1624 metres, superseded at its completion in 1998 only by the Akashi–Kaikyo Bridge in Japan which had just been completed 2 months previously.

2 Aesthetics

Following the view of Fritz Leonhardt, in Ref. [1], bridges can be assessed and analysed for aesthetics against ten sets of criteria or rules. This paper will now look at these criteria in the context of the East Bridge.

Most importantly a bridge should fulfil its function. It should be obvious even to non-engineers how the bridge works, inducing confidence in the user. The East Bridge is an excellent example of this, clearly showing off its strength in the form of a suspension bridge with large catenary cables and tall substantial pylons. Another exciting aspect of the function of this bridge is the way the concrete pylons and anchor blocks emphasize the load path of the structure (see Fig. 3).

Proportions give bridges balance in their geometry. The proportions of this bridge are aesthetically pleasing; the deck has a relatively slim depth and contrasts well with the stockier towers.

The order of the bridge should also be considered. Too many disruptions along the edges and lines of the bridge upset the simplicity of the bridge. The repetition of the cables gives the East Bridge good order, and due to their slender appearance they do not obstruct the view through the bridge. One criticism could be that the lines of the abutments are too complex and clash with some of the other column lines however this is negated by their excellent fulfilment of function.

As with all designs refinements improve the appearance of a bridge. The shape of the steel box girder on the East Bridge ends with a thin edge giving the deck a slender smooth appearance.

Another refinement is that the deck is suspended across the whole 2.7 kilometres of the bridge, rather than supported at the towers, eliminating the need for bearings or suspension pendulum rods. This meant that the intermediate cross beam on the towers could be placed at mid-height which improves the proportions of the towers. The towers are also further refined by flaring the legs to allow for protection from ships rather than using stone islands.

It is important that the style of bridge proposed fits in the location in which it is built. Due to its long central span the elegantly slim silhouette of the bridge deck hovers beautifully above the impossibly wide Great Belt strait and rises gently from the flat islands that the Great Belt divides.

Texture is often ignored in bridge design but on the East Bridge the contrast of the rough concrete towers and the smooth steel deck emphasize its proportions especially when viewed at sunset or when the light reflects off the surface of the water (see Fig. 4).
Colour can be used either in a quite obvious way or in a more subtle way to highlight elements of the bridge. On the East Bridge it has been used in quite a subtle way, the concrete is stone grey which when coupled with the bright blue backdrop of the strait and the sky evoke images of rocky cliffs. The bridge has dark grey cables that either contrast with the background or blend in, depending on the nature of the light, finally the shape the deck and the piers which make the most of the contrast between shadows and light.

Character can be quite hard to define and can depend on individual opinion. It is perhaps not applicable to the East Bridge but should nevertheless be considered when assessing the aesthetic qualities of a particular bridge.

Complexity can be stimulating if used appropriately, however too much complexity can look chaotic. The simplicity of the East Bridge is what makes the bridge appear so stunningly elegant. The thin line of the deck curves gracefully and the geometrical shape of the closed section has also been kept very simple.

Some bridge designs take inspiration from nature or even try to blend into the natural environment around them. The East Bridge is more of a statement of the engineering achievements of which man is capable. Therefore it would be inappropriate for the East Bridge to incorporate nature into its design.

A beautiful bridge does not necessarily fulfil all ten rules, just as an ugly bridge does not necessarily break all ten rules. The important thing is that when observing the bridge it brings immediate pleasure to the eyes. In this respect the East bridge is a very aesthetically pleasing bridge.

3 Structural Design

The bridge design was led by a CBR joint venture of COWI Consulting Engineers and Planners, B. Hojlund Rasmussen and Ramboll & Hannemann. Danish architects Dissing and Weitling provided all aesthetic contributions to the design.

The Great Belt is an international shipping route and hence is subject to a large volume of ship traffic, about 20,000 vessels per year. A study was completed involving theoretical ship-collision as well as simulations of actual navigational conditions. These studies indicated that the main span should exceed 1.5 kilometres (see Ref. [2]). This meant that a suspension bridge was the only realistic solution to meet the main span requirements. By optimizing the design, a 1624 metre main span with 535 metre side spans, carrying a four lane motorway plus emergency lanes was finally selected. The final dimensions of the bridge can be seen in Fig. 5.

3.1 Superstructure

3.1.1 Girder

The welded steel box girder is continuous between the anchor blocks over the whole suspension bridge length of 2700 metres. Hence there are expansion joints located at the anchor blocks but there are no expansion joints at the towers. Vertical elastic support is exclusively provided by the hangers. This eliminated the need for bearings at the towers which would require maintenance.

The form of the box girder lends itself well to prefabrication and also helps with the bridges aerodynamic performance. Transverse trusses inside the deck improve the decks fatigue resistance. The inside of the deck is also protected from corrosion by dehumidification.

3.1.2 Cables

A cable sag ratio of 1:9 was decided to be optimum to reduce sliding forces in the anchorages. The main cables are 3079 metres long. Each cable consists of 37
strands which in turn are made up of 504 high tensile galvanized wires, which are 5.38 millimetres in diameter. The cables are also protected by wrapping a steel wire around the cables which is laid in a zinc paste. These were constructed using a modified version of the traditional aerial method (see Fig. 6).

The bridge girder is supported every 24 metres by pairs of hangers. The hanger cables are protected by a polyurethane sheath. The hangers have been designed so that one pair of hangers can be removed whilst being replaced, without disrupting the traffic on the bridge.

3.1.3 Pylons
The reinforced concrete pylons reach a height of 254 metres, breaking previous records set by the Humber Bridge. This was a result of the unusually large cable sag ratio. The pylons have also benefited from a number of aesthetic refinements particularly the traditional cross beam below the deck thanks to the continuous box girder.

3.1.4 Anchor Blocks
The anchor blocks are open structures. This was a result of aesthetic input but has practical advantages too such as reducing the amount of concrete needed and also the open shape meant that during cable spinning the anchor blocks could serve as wire handling areas.

4 Construction
The Contractors included Hochtief and E.Phil and Son for the foundations, concrete towers and anchorages as well as a consortium led by Italian contractors CMF Sud for the main cables, hangers and the box girder. The start of construction was delayed; setbacks on the construction of the rest of the fixed link meant that the West Bridge and the tunnel were behind schedule preventing works on the East Bridge from getting underway.

To make matters worse Finland decided to seek an injunction before the International Court of Justice at the Hague to stop the East Bridge from going ahead. Although Denmark had notified other maritime nations of the bridge earlier in 1977, in 1991 Finland requested a redesign of the bridge as the clearance height of 65 metres was not sufficient for the passage of Finnish offshore drilling rigs. By September 1992 the matter was solved, the East Bridge design would keep the clearance height of 65 metres but the Danish government had to pay Finland $15 million in compensation. Eventually construction began. Five years later, just over a year later than planned, it was completed.

4.1 Preliminary Works and Foundations
Great importance was placed on the environmental effects of the bridge, In particular how the new bridge would affect the flow of water through to the Baltic Sea. In 1987 the Danish parliament passed an act determining that the water flow should remain unaffected by any new construction and so a “Zero Solution” was adopted.

The design of the anchor blocks was streamlined, saving 700,000 cubic metres of compensatory dredging. The completed fixed link has a blocking effect which represents a total 0.5 per cent of the total water flow through the Great Belt.

Therefore to minimise the blocking effect that the bridge has on the flow of the great belt, 8 million cubic metres of sand and clay were dredged in compensatory dredging. All the dredged materials were used in the construction of artificial islands for the anchor blocks or placed for land reclamation on the island of Sprogo. The area of reclaimed land on Sprogo is 116 hectares which is three times the size of the original island of Sprogo (see Ref. [3] and Fig. 7).

The geology in the Great Belt region consists of layered strata of tills underlain by palaeocene marl followed by limestone. Fig. 8 shows a geological section through the adjacent Great Belt tunnel and is
representative of the geological section through the East Bridge. The tills are stiff to hard clays with some boulder clays from meltwater deposits. The marl varies from a weak marl stone to a moderate weak marl stone.

Initially it was revealed that at 2 to 3 metres below the sea bed there was a layer of very dense glacial till. However subsequent borings revealed underlying weak strata at 8 metres below sea level, probably the relics of thawed ice lenses left from the glacial period. Therefore the foundations for the pylons and anchor blocks required dredging out zones of weak material and backfilling with compacted stone.

4.1.1 Pylon Foundations

The water depth around the Pylons is 20 metres. A 10 metre layer of soft till was excavated before placing a 5 metre deep screeded trimmed bed of crushed stone.

The Caissons have steel skirtings that are 0.5 metres tall that penetrate into the stone bed by 0.3 metres. The contact between the stone bed and the Caissons is ensured by grouting.

![Figure 9: Various parts of the anchor block foundations.](image)

4.1.2 Anchor Block Foundations

It was necessary to excavate to 22 metres below sea level into the clay to construct a wedge shaped gravel foundation base that could cope with the large horizontal loading. To reduce the shear stress at the interface and stop sliding along a thin weakened zone of excavated boulder clay surface, two wedged shaped stone beds inclined at 16 degrees were constructed. These wedges support the front and rear third of the anchor block (see Fig. 9). Contact between the anchor block caisson and the gravel wedges is also ensured by grouting below the base.

4.2 The bridge takes shape

![Figure 10: Towing a pylon caisson](image)

Once the foundations had been prepared the caissons could then be placed. The cellular pylon caissons 78 by 35 metres and 20 metre tall weighed about 30,000 tonnes. The anchor blocks caissons too are quite large, covering an area of 6100m² and originally weighing 36,000 tonnes. The caissons for the pylons and the anchor blocks were cast in a dry dock 55 kilometres away from the bridge site. The dry docks were then flooded and breached allowing the caissons to be towed to the site. Fig. 10 shows a pylon caisson being towed to the site in April of 1993. The anchor blocks arrived at the site later that year in October. See Fig. 11.

![Figure 11: The anchor block caisson](image)

Once the caisson were towed to site they were manoeuvred into position using large winches then sunk to the required depth and placed on the beds of compacted stone. The pylons caissons were filled almost entirely with heavy sand called olivine whereas the anchor block caissons were ballasted with sand at the front and ballasted with olivine at the back where the cables are situated.

The pylon caisson top was 6 metres below sea level so a steel cofferdam was used to cast the pylon base up to 21 metres above sea level. The anchor block caisson tops were 4 metres above sea level. From this level the rest of the anchor block was then cast in-situ up to its full height.

After 21 metres the pylon splits into two inclined legs. The legs were constructed in 58 lifts of 4 metres using “self climbing” formwork (see Fig. 12). The formwork was made up of seven working levels for fixing reinforcement, concreting, operating and finishing. The concrete was supplied to the site via regular ferry services.

![Figure 12: The reinforced concrete structures being cast.](image)
Once the concrete structures were completed the main cables could then be hung. It was decided by the contractor not to use prefabricated parallel wire strands but to use a modified type of aerial spinning called the controlled tension wire adjustment method. This modification was less time consuming and less sensitive to weather conditions such as heavy wind compared with the traditional free-hanging wire method. Spinning began on the 6th of July 1996 and carried on 24 hours a day for a record breaking four months, finishing seven weeks ahead of schedule.

Figure 13: A barge carrying two girder segments.

By the spring of 1997 the hangers had been installed on the bridge and the girder segments, which had been assembled in Portugal and Italy into lengths of 48 metres, were now being stored 200km from the bridge site. The girders were transported to the site by barge (see Fig. 13). The girder sections were then hoisted into position by two cranes that were above the main cables (see Fig 14).

Once the girder section was in position it was temporarily clamped to both the neighbouring section and to the main cables, before welding the sections together. Once the girder sections were erected the deck was sand blasted, an adhesive applied, a damp proof course laid over it and two layers of mastic asphalt on top. Guide vanes were also installed on the bridge using space frame gantries supported off the bridge deck.

Figure 14: A girder section being lifted into position.

5 Loading

The bridge was designed in accordance with Danish standards which will soon be superseded by Eurocodes. However for the purpose of analyzing the bridge this paper considers BS 5400.

5.1 Dead and super-imposed dead loads

The dead load for the bridge includes the weight of the steel deck, the hangers and the cables. Whilst the super-imposed dead load comprises the surfacing and fill, the crash barriers and guard rails as well as the wind guide vanes. The mass of the girder including cables is 22.74x10^3 kg/m. See Ref. [4]

5.2 Live traffic

5.2.1 HA Loading

Based on known dimensions of the bridge cross section it can be assumed that the carriage way width is approximately 11.3 metres either side of the bridge, 22.6 metres in total. Thus giving 3 notional lanes either side (6 in total). Hence the width of the notional lane is about 3.8 metres wide. Since the bridge has a span of 1624 metres then the unfactored HA loading is given by 9kN/m / 3.8m = 2.4kN/m² and the knife-edge load per notional lane is taken as 120kN. Two lanes are loaded by the full HA loading whilst the other four lanes are loaded with 1/3 HA loading.

5.2.2 HB Loading

Given that the bridge has a long central span a HB vehicle with a middle dimension of 6 metres must be considered to create the most adverse loading effect. Since HB loading is considered to be 45 units, this would give 112.5kN nominal loading per wheel for the vehicle shown in Fig. 15

Figure 15: HB Vehicle Layout

5.3 Other Vehicle Loadings

The bridge design will have also had to take into account braking and acceleration forces as well as vehicle collision loadings with the barriers. There is no pedestrian access to the bridge.

5.4 Ship Impact

Due to busy navigational channel that the bridge crosses, ship impact was considered to be one of the most important loads on the substructure of the bridge. The anchor blocks and pylons were designed to resist impacts of ship of up to 250000 dead weight tonnage travelling at up to 10 nautical miles an hour or about 5.14 metres per second without any permanent deformations or movements. See Refs. [5,6]. The anchor blocks in particular are also protected by the construction of artificial islands around them.

5.5 Snow

Heavy snow falls are often experienced during winter at the Great Belt. Snow live load may not be analyzed
simultaneously with traffic live loads as it is likely that the bridge is closed during road clearing. However during the design of the bridge the effect of snow accumulating along railings, either naturally or from snow ploughing was considered to have a detrimental effect on the aerodynamics of the bridge (see Ref. [4]).

5.6 Other Load Effects

Other effects also need to be considered in the bridge design when designing for the worst load case in the lifespan of a bridge. These include construction loads, stress relaxation of cables, settlement of supports, wave impact and water flow.

6 Temperature Effects

The girder is a continuous length between the anchor blocks for a total of 2700 metres. The temperature can range from -5 to 30°C. Since in Eq. (1);

\[ \Delta L = L \Delta T \alpha. \]  

and \( \alpha = 12 \times 10^{-6}\,^\circ\text{C} \) then \( \Delta L = 2700 \times 35 \times 12 \times 10^{-6} = 1.1\,\text{m} \). However in Ref. [6] Sketterup states that the expansion joints have to allow for movements of plus or minus 1 metre.

7 Wind Loading

The wind climate and design assumptions were taken from the Danish code of practice (DS 410.3, 1982). For 9 consecutive years prior to design 10 min mean wind speeds \((U_{10})\) were measured at an altitude of 70m which is equivalent to the height of the bridge deck. Other recordings of gust speed \((U_g)\) and of turbulence spectra were also acquired before design. The key wind parameters that were adopted for tender design are shown in table 1 and compared to the corresponding values that are stated in DS 410.3.

| Table 1: Design wind speeds \(U_{10}\) and \(U_g\) at 70m level predicted for a 100 year return period, from Ref. [4] |
| --- | --- | --- | --- |
| East Bridge | DS 410.3 | | |
| \(U_{10}\) (m/s) | \(U_g\) (m/s) | \(U_{10}\) (m/s) | \(U_g\) (m/s) |
| 38.9 | 49.8 | 42.2 | 47.7 |

In Ref. [4] Larsen outlines three of the aerodynamic problems which received particular attention during the design of the bridge: Aerodynamic instability (flutter), Buffeting and Vortex shedding excitation. Three wind tunnel tests were developed to test the bridges ability to cope with these aerodynamic problems; a 1:80 scale section model, a 1:300 scale taut strip model and a 1:200 scale full aeroelastic model.

It had already been decided that a box girder would be used for the bridge deck and a trapezoidal cross section was thought to be the best shape to combine structural and aerodynamic requirements.

During the section model test 16 variations on the trapezoidal box section were tested to see how modifications to the sections geometry influenced the aerodynamic stability. Once the geometry of the section had been chosen this section was tested at 1:200 scale which meant building a purpose built 14m wide wind tunnel at the Danish Maritime Institute. In table 2 it can be seen that the estimate of the flutter wind speed is quite consistent between all three tests and is about 70m/s. 70m/s is about twice the speed of the greatest wind speed recorded at the site (see Ref. [6]).

| Table 2: Flutter wind speeds \(U_c\) obtained from section model, taut strip and full bridge tests, from Ref. [4] |
| --- | --- |
| Type of test | Critical wind speed \(U_c\) (m/s) |
| Section Model | 70-74 |
| Taut strip | ~72 |
| Full bridge | 70-75 |

7.1 Natural Frequency

The natural frequency is the frequency for which large amplitude oscillations will occur in a structure. These large amplitudes can cause failures in structures such as bridges.

For the main bridge 9 modes were calculated in Ref. [4] to find the first three modes for vertical, lateral and torsional. These are presented with their associated natural frequencies in figure 16.

For the approach spans we can say that as a rule of thumb \(f = 100 / \text{span length} \) for the first vertical mode for box girder steel beam bridges. So in this case where the approach span lengths are about 193m \( f = 0.52 \text{ Hz} \) as stated in Ref. [7] this leads to a \( U_c \) of 18 m/s which is much lower than the design speed of the bridge and a vertical peak response of 0.4m. This then led to the need to design a Tuned Mass Damping system.
7.2 Tuned Mass damping

The approach spans of the bridge are very slender with span to depth ratios of 27.2 (see Ref. [6]). A 1:125 scale aeroelastic model of the whole of the multispan approach bridge was built and wind tunnel tested in Ref. [8] with the purpose of investigating and reducing vortex induced oscillations on the approach bridge. Tuned Mass Dampers were modelled at the centre spans and results showed that they had been successful in damping the oscillations for the first six vertical bending modes in smooth and turbulent flow. When the bridge was built, tuned mass dampers of approximately 0.5% of the modal mass of the approach bridges were installed on spans where, for given modes of vibration, the largest motions will occur.

7.3 Vortex Induced Oscillations

In Ref. [4] Larsen noted how guide vanes installed underneath the deck had been very effective in suppressing vortex shedding excitation of the main span during the wind tunnel tests. However it was decided that these would not be installed on the bridge but could be considered as a retrofit measure should this seem necessary later on in the operational life of the bridge.

It was during the welding of the girders that vortex shedding oscillations were first noticed but it was hoped that these would cease once the bridge assumed its final dead load condition after road surfacing works. Unfortunately this was not the case. In Fig. 17 we can see how visible these oscillations were during the roads surfacing works by observing how the circled parked car becomes momentarily obscured by the horizon.

![Figure 17: Vertical Oscillation of East Bridge, Ref. [9]](image)

During the design process a theoretical finite element study of vortex induced oscillations had made it clear that these oscillations were structurally insignificant and would not cause collapse. However in Ref. [9] a concern was expressed that the public would lose confidence in the structural reliability of the bridge resulting in a loss of traffic volume.

An improved design of the guide vanes proposed by Larsen in Ref. [4] was wind tunnel tested at 1:60 scale. The design consisted of curved steel plates supported at 2m intervals over 1400m of the central portion of the main span.

![Figure 18: Guide vanes as installed on the East Bridge](image)

These guide vanes were installed early in 1998 prior to the official opening of the bridge later that year in June. Frequent inspections of the bridge continued and after 9 months of being in operation it was observed in Ref. [9] that the bridge no longer suffered from vortex induced oscillations and that the guide vanes had been successful in efficiently suppressing vortex induced oscillations.

Before the guide vanes were installed full scale measurements were conducted by Frandsen in Ref. [10] of the amplitude of the vortex induced oscillations on the bridge. For the first time at full scale simultaneous measurements of wind speed, wind direction, deck pressures and accelerations of the deck were recorded. Frandsen hoped by gaining further insight into wind induced phenomena, a change in the design rules (BD 49/93 design rules for aerodynamic effects on bridges) would include a decrease in the acceleration limit and the structural damping value that is used for steel box girder decks of suspension bridges. In 2001 BD 49/93 was superseded by BD 49/01 and entailed a number of changes including improved consideration of edge details, amendments to all critical wind speeds, improved accuracy of vortex shedding amplitudes and more accurate criteria for aerodynamic susceptibility.

8 Strength

As a suspension bridge the Great Belt East Bridge gets its strength from the parabolic shape of the main cables. This system has the greatest strength when it is loaded under uniform symmetrical loading.

The deck which is in compression is supported by hangers which are then put into tension and thus loading the main cables. The shape of the main cables only allows the steel cables to be under tension forces, which is extremely efficient given the high tensile strength of steel. The wires used for the cables have a tensile strength of 1570MN/m². These tension forces are carried over the towers, which put the towers into compression, and then are carried to the anchor blocks. See Fig 19.

The anchor blocks stabilise the tensions forces in the cables through gravitational compression through to the foundations. The interaction of the anchor blocks with its foundations also helps it resist the lateral forces from the cables. In the case of the East Bridge the cable forces that the anchor blocks can resist are up to 600MN. To the rear of the anchor blocks the cables are anchored in concrete massifs 10 metres wide and 30 metres high. Each massif is also pre-stressed in addition to the un-tensioned reinforcement with 444 bars with a force of 470MN.

![Figure 19: Forces diagram](image)

9 Serviceability and Durability

It was important during the design that the long term maintenance and lifetime costs of the bridge were reduced as much as possible as well as the construction costs. This has resulted in the design of a bridge that is durable and with a long service life.
One of the main design features of the East Bridge which ensures a longer service life is the continuous box girder through the pylons. This limits the number of expansion joints required, whilst also reducing the deformation from traffic loads by 25% (see Ref. [2]) and also reduces the deflections due to lateral wind loading. Due to the large expansion section of nearly 2700 metres, hydraulic buffers were also installed between the anchor blocks and the girder. The hydraulic buffers partially restrain longitudinal short term movements but allow slow movements under temperature fluctuations. Most expansion joint wear in bridges is produced by small movements due to traffic. At the mid-span of the East Bridge the cables are clamped to the stiffening girder. The buffers combined with the central clamp prevent “fast” longitudinal girder movements. This allows a short bearing slide, so there is a lot less wear in the expansion joints due to traffic and wind. Elimination of relative movements between the girder and the main cables also reduces the risk of fatigue loading on the short hangers in the mid-span of the bridge.

The design of the bridge has been kept quite simple geometrically, for example the closed box girder with smooth exterior surfaces. This means that the exposed surfaces are kept to a minimum, as exposed surfaces can be quite sensitive to deterioration, but are also quite easy to inspect and clean. The interior of the box girder, which has about 80% of the total steel used on the bridge (see Ref. [12]), as well as the splay chambers for the cables and the cable saddles at the top of the towers are protected from corrosion by dehumidification and so don’t need to be painted. Steel can corrode at about 60% relative humidity so to allow for local fluctuations these areas are kept at an average of 40% relative humidity. The main cables are protected by wrapping a wire laid in zinc paste whilst the galvanized hangers are protected by an 8mm thick polyurethane sheath. The hanger cables are also protected from salt spray from traffic at the connection with the girder by a steel tube anchorage.

The concrete structures on the bridge have been designed for a life of 100 years (see Ref. [6]). To prevent corrosion of the reinforcement steel, there is a substantial cover thickness particularly in the splash zone, where the reinforcement cover is 75mm. The reinforcement is also connected electronically and the level of carbonisation is monitored by corrosion monitoring cells. If the carbonation reached the reinforcement then a cathodic protection system would start.

To ensure that a bridge is still serviceable in weather conditions where there are high wind loads it is important to have quite a stable design that can resist these wind loads. The concrete pylons have massive flaring legs and two struts which coupled with the gravitational weight of each tower (190,000 tonnes) absorb the wind loads from the structure (see Fig. 20). The girder is aerodynamically designed to cope with wind load. The closed box design with interior transverse trusses also helps improve the fatigue resistance of the deck.

The bridge also has a structural monitoring system installed which is maintained by COWI.

10 Accidental and Intentional Damage

It is extremely unlikely that the bridge would ever be the subject of intentional damage due to its location. The East Bridge is located in a largely rural area of Denmark and the bridge is only accessible by vehicle. The 2008 global peace index ranks Denmark as the second most peaceful country in the world (after Iceland) and vandalism and crime are generally at quite a low level in the country.

However accidental damage can never be ruled out. Ship impact has always been a concern for the bridge. The nearby West Bridge has had two ship collisions since its completion although none of these caused structural damage. So far the East Bridge has escaped with one near miss. On the 16th May 2001 the bridge was closed for 10 minutes while the navy deflected a 27,000-ton bulk carrier from colliding with one of the bridges anchor blocks.

There is also a risk from explosives in the Great Belt left behind after World War II. During construction a British World War II explosive was discovered containing more than 300kg of dynamite. It was towed away and safely detonated.

11 Conclusions

The bridge was completed late, and with a cost of $1.1 billion, over budget. However the bridge has proved very popular and during the opening celebrations 275,000 people turned up to cross the bridge by foot, bicycle or other methods! The bridge represents the largest engineering feat so far to be completed in the small country of Denmark and the Danes are justifiably proud of it. The bridge was the last piece in the puzzle to linking...
their country together and has cut journey times across the Great Belt by an hour.

Apart from the benefits that the bridge offers to the Danish people it has also contributed greatly to bridge engineering particularly in relation to long span cable structures. Elements resulting from the East Bridge such as the revolutionary continuous box girder span, new developments in aerial spinning, as well as a developed understanding of aerodynamic behaviour of cable supported structures has revolutionised the way long span bridges will be designed in the future.

The East Bridge celebrated its 10th birthday in 2008. It is still the longest spanning bridge in Europe, although later this year it will slip to third longest spanning bridge in the world with the completion of the Xihoumen Bridge in China. Yet despite its colossal size, the East Bridge of Denmark has a grace and an elegance that will be difficult to match.

Figure 20: The Elegance of the East Bridge

11.1 Future Changes

Whilst there are no plans to make any adjustments to the structure of the bridge, the owner of the bridge, Sund and Baelt, is conscious of the bridges environmental impact. With that in mind a wind farm just north of the islands of Sprogo, which will contribute to the electrical consumption of the Great Belt Fixed Link, is under construction. The wind farm will consist of 7 Wind Turbines each with a capacity of 3MW. It is hoped that these will be built in time for the United Nations climate change summit in Copenhagen at the end of 2009.

11.2 Suggested Improvements

Original legislation in 1973 had called for the link to carry a six lane motorway instead of the four lane motorway that was actually built. Since the link was built, traffic crossing the Great Belt has increased on average from 8000 cars per day to 30,200 cars per day. During busy summer periods the traffic can be as much as 40,000 cars a day. Since the bridge deck is quite wide it could accommodate additional lanes, so an improvement could be upgrading the link to a six lane motorway. However it is often found that the construction or improvement of transport infrastructure creates its own traffic and therefore this may not be the best solution.

11.3 Denmark's Ambition

The Great Belt East Bridge is the most spectacular so far in a series of engineering successes to link the islands of Denmark as well as Scandinavia with mainland Europe. With the completion of the Oresund link in 1999, the next stage to the realisation of this ambition is the construction of the Fehmarn link between Denmark and Germany. At the moment competing consultancies have so far come up with designs for a multispans cable stayed bridge, a suspension bridge as well as a tunnel crossing. Clearly the East Bridge was not the first large construction project to be completed in the small country of Denmark and nor will it be the last.

12 References