A CRITICAL ANALYSIS OF THE ORESUND BRIDGE LINKING SWEDEN AND DENMARK

C.J. Shrubshall[1]

[1]*University of Bath*

Abstract: This article provides a critical analysis of the Oresund Bridge, constructed in 2000 in order to link the Oresund region between Sweden and Denmark. It illustrates the aesthetics, loadings, strength, serviceability, construction technique, durability and susceptibility of the bridge to intentional or unintentional damage.

Keywords: *Oresund, crane construction, prefabrication, cable-stayed, double layer, road and rail*

1 History

The Oresund Bridge linking Malmo in Sweden with Copenhagen in Denmark was opened to traffic on the 1st July 2000. The bridge is part of a 17 km crossing also consisting of a submerged tunnel and manmade island making up the other half of the link. With a main span of 490 metres the Oresund Bridge is the both longest cable-stayed bridge carrying both road and rail traffic and has the highest freestanding pylons in the world.

Figure 1: Oresund Bridge, main span

Plans to link the Oresund region have been around for centuries but had always previously come up against strong opposition. Firstly in the 19th Century the plans were opposed by nationalists in both countries and more recently by environmentalists concerned with the impacts construction would have on the wildlife in the area surrounding the Oresund region.

When the plans to build a link between Sweden and Denmark were approved George Rothne was appointed as the designer and Arups as the engineers.

2 Reasons for the bridges construction

According to Ref. [1] the governments of both Sweden and Denmark felt that by linking Malmo and Copenhagen they would be creating a region with increased cultural, educational and economic links. The region would benefit from increased business and economic activity and it is possible that with the regions expertise in Information Technology and Biomedicine it could become one of Europe's leading 'knowledge centers'.

From Ref. [2] in recent years the rate of unemployment has been higher in Malmo than in Copenhagan. With the construction of this link it is now possible to work in one country and live in the other. As housing is cheaper in Malmo than Copenhagen people are now able to purchase houses in a cheaper area and commute across the bridge to work.

With Europe becoming increasingly borderless the governments of Sweden and Denmark see the Oresund region as a model of integration and cross border cooperation for the rest of Europe.

3 Reasons for cable-stayed construction

The reasons for constructing a cable-stayed bridge rather than a suspension bridge linking the Oresund region were the same as have always been. The spinning of the main cable on a suspension bridge is expensive and tricky where as cable-stayed bridges carry a much more direct load path through the cables to the pylons, stiffening the bridge further. This extra stiffness is especially useful as the bridge is carrying rail traffic, which requires less deflection than would be acceptable for a road bridge only. If the bridge had been hung from a main cable the deck would have had much lower bending stiffness and therefore a higher deflection.

The cable-stayed design also lends itself to the method of construction used on this bridge, although it could have been adapted to work with a suspension-type bridge.

4 Aesthetics

The analysis of the aesthetics of any object is very much personal opinion. However, using Fritz Leonhardts ten ‘rules’ of aesthetics to be considered in bridge design it is possible to assess the areas in which the Oresund Bridge succeeds aesthetically.

4.1 Fulfillment of Function

The use of a cable-stayed bridge allows the structure and load paths to be seen clearly. The symmetry of the cables about the piers gives a sense of balance seen in most cable-stayed bridges. However, the combination of the cables and trussed deck could be seen as a confusion of structural elements. As the approach bridges consist of trusses of the same depth it looks slightly strange to suddenly have cables supporting the truss. The truss and cables are of course required on the main span as it maintains the continuity of the deck from the approach bridges.

4.2 Proportions

There are no obvious disproportions within the bridge. In my opinion I think bridges with a thinner deck look more aesthetically pleasing. Although the deck is not solid on the Oresund bridge I think it still suffers from the deck being slightly too deep. The advantage of the deeper deck is that the bridge pylons can be much thinner, as the deck is acting as the main structural element. I tend to think bridges look nicer with thinner decks and thicker piers, however the Oresund Bridge is the opposite way round.

4.3 Order

There are lines and edges created by truss construction of the deck, but these are not unnecessary lines and cannot be seen from a distance. The truss deck is of good order and of the same size along the length of the bridge, even as it crosses the main span. The bridge incorporates simple, square pylons, which are not joined at the top. Perhaps joining these columns would allow them to be even more slender. This would not necessarily improve the aesthetics of the bridge and could leave the bridge looking out of proportion. The cables are arranged in two parallel planes and so look as good as possible when viewed obliquely. The only improvement on this arrangement of cables would be to have only a single plane of cables, as in the Millau Viaduct. However, this would change the dynamic of the bridge and other changes would have to be made also.

4.4 Refinement

With most tall columns it is usual to taper them towards the top to prevent them looking wider and therefore illogical. The pylons of the Oresund Bridge are tapered towards the top. This tapering is also more efficient structurally as the columns take less compressive force towards the top.

The approach bridges are varying heights from the water, however the spans remain constant. This means that the aspect ratio between the water, piers and deck is not constant and could be seen as less aesthetically appealing. In order to create constant aspect ratios the spans would have to be made different lengths, this is perhaps not practical in terms of the prefabricated construction method used (section 5).

4.5 Integration into the environment

Over an open span of water cable-stayed bridges often look aesthetically pleasing. The bridge is curved in plan and this could be seen as an attempt to fit the bridge into the environment by using a less rigid shape.

4.6 Surface texture

The surface texture on a bridge such as the Oresund was probably overlooked in its design. I do not see this an oversight, as it seems unnecessary to look into surface textures on a bridge where no one gets close enough to notice. On smaller bridges and pedestrian bridges texture can be very important as people can see and touch it but on a bridge of this size it is not the most dominant aesthetic characteristic.

4.7 Colour

In some trussed bridges it has been shown that painting the truss red both separates the trussed components and gives an aesthetic appeal. The

Oresund Bridge has not had colour used in order to separate its components.

Figure 2: Golden Gate Bridge, use of red on steel elements

George Rothne, the designer of the Oresund Bridge was keen to use black for the truss as it gives a variety of different colours in different lights, Ref. [1]. Colour is not used to great effect to separate components in the Oresund Bridge, however the cables are a dark colour, perhaps this makes them more visible than in bridges such as the Second Severn crossing, where the cables are a blue in order to make them disappear against the sky. I think this can sometimes be shame as it is nice to be able to see the cables, as it gives the pylons are purpose.

4.8 Character

The Oresund Bridge does seem to lack a certain amount of character. Part of the reason for this is the bridges uniformity. This uniformity leaves the bridge lacking in flamboyancy and could be seen as slightly boring.

It seems at first glance that the bridge is a standard cable-stayed design. I think part of the bridges character is made up of the way in which it was built, almost like a Lego set, with individual components being stuck together. That is what I feel gives this bridge some of its character and it is a shame people are not aware if the incredible way it was built.

4.9 Complexity

The only way in which the Oresund Bridge shows any complexity is in the interaction between the cable-stays and the trussed deck. The stiffness of the deck carries some of its own weight and so the cables are not completely supporting the deck. This is the sort of complexity that would not be obvious at first glance, in a similar way to the bridges character.

4.10 Incorporation of nature

It is hard to say that the Oresund Bridge incorporates nature in any obvious way. The bridge is curved in plan, Fig. 3, which in my opinion is more aesthetically pleasing than a straight bridge and perhaps safer for road users as they are forced to concentrate slightly more. Whether this curved plan is incorporating nature or merely responding to it is not clear.

Figure 3: Satellite image of Oresund link

4.11 Conclusion

The Oresund Bridge does not catch the eye in the same way that a bridge such as the Alamillo Bridge in Seville does. It does not have the same amount of character and complexity. However, it does conform to many of the ‘rules’ that can make bridges beautiful. This bridge is much more about practicality, both in the way in which it was built and the purpose it serves (carrying both road and rail traffic), than its aesthetics.

5 Construction

Construction of the Oresund Bridge was not novel in that prefabrication has been used for decades. However, prefabrication on this scale is what makes the construction of the Oresund Bridge incredible.

Everything from the piers and caissons to the trussed deck were fabricated on-shore and transported to the bridge line. The only part of the bridge constructed insitu was the main piers.

5.1 Prefabrication

There are many advantages in using prefabrication on the scale used in constructing the Oresund Link.

As with any medium to long span bridge encouraging competitive tendering can be a problem. There are not always a large selection of Contractors with the resources and skills to carry out insitu construction on this scale. By planning to have as much of the bridge fabricated on shore as possible there were suddenly many other concrete Contractors that were able to tender for parts of the bridge. This in turn drives the price down and leads to a cheaper form of construction.

Opponents to the construction of this bridge were critical of the impact it may have on the surrounding wildlife. By prefabricating bridge components the risk of polluting the water during construction was greatly reduced along with the amount of time spent at the bridge line.

The bridge was completed on schedule, often rarely seen in large construction projects. This was mainly due to the use of prefabrication. Casting the bridges components is far quicker and easier on-shore than at sea and the added advantage of superior quality control means that the elements are often of a higher standard than when cast insitu.

The Oresund straight separating Denmark and Sweden is a busy shipping region and it was important to minimise the disruption to this traffic. By using prefabricated elements the amount of time spent on the water was reduced along with any risks of disruption.

It is hard to find fault with the prefabrication method used in the construction of the Oresund Bridge. The bridge was completed on budget and within schedule and the quality of the final product was not compromised.

Perhaps if the heavy-lifting sea-going crane, which was used to carry the elements to the bridge line, were not available the method of construction would have had to be different. As the crane was a very specialised piece of equipment it is likely that it was very expensive to acquire for the duration of the build. The savings made in prefabricating the separate bridge components, which was necessary to satisfy environmental regulations, could have been cancelled out by the cost of using such a specialist piece of equipment, making the construction method far less cost effective.

One of the main risks associated with this particular form of prefabrication are those involved with the transportation of the components. The approach bridge piers and caissons were constructed in dry docks at Malmo and so only needed transporting to the bridge line. The caissons were too heavy for the crane to lift and so were towed out to the bridge line and sunk.

Whilst there were risks involved with this there were other components such as the approach trusses and main span trusses which were constructed in Cadiz, Spain and Karlskrona, Sweden respectively, which had to be shipped by ocean going barge to the docks in Malmo. There would be dramatic effects on both the schedule and cost of the bridge if anything had gone wrong in the components transit.

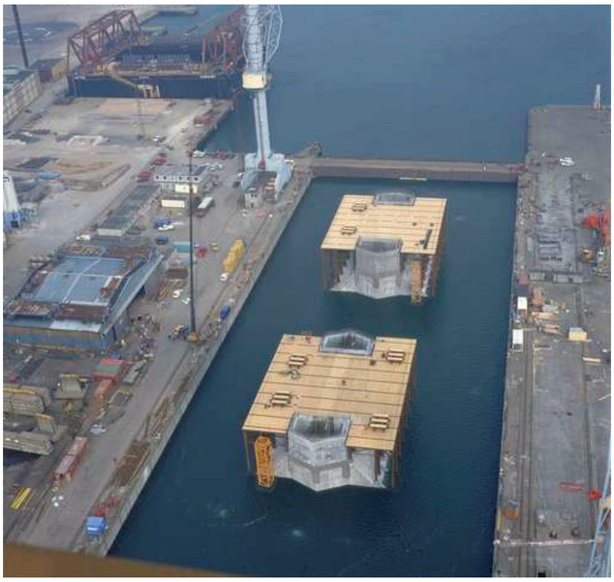

Figure 4: Pier caissons ready to be floated to bridge line

The other issue with transporting bridge elements to the bridge line is the weather. Restrictions would be placed on the Contractors as to the conditions in which they are able to transport elements. This will have affected the schedule and therefore the budget. The best time to transport the elements will have been during the summer when the weather is calmest. The casting should have taken place in the winter to allow them to be ready in summer.

5.2 Construction Technique

Figure 5: 'Svanen' placing a pier in the bridge line

Once the bridge elements had been fabricated on-shore they were transported to the bridge line using a heavy lifting vessel called 'Svanen', with the exception of the caissons.

This catamaran-type vessel has a lifting capacity of 9500 tonnes. In order to make prefabrication of the trussed girders efficient advantage was gained by using repetitive spans. All of the approach bridges are either 120m or 140m spans.

In order to construct the approach bridges the piers were dropped onto their caissons and then the trussed sections placed on top. The main span was constructed in a slightly different manor in order to overcome the longer span.

5.3 Analysis of crane 'Svanen'

In order to give an idea of the sorts of forces and moments that the giant sea-going crane 'Svanen' is subjected too the calculations below have been carried out. These assume a simplified model of the crane and that it is carrying its maximum load of 9500 tonnes. The dimensions used in these calculations are estimated and used just to give an idea of the loads that the crane resists.

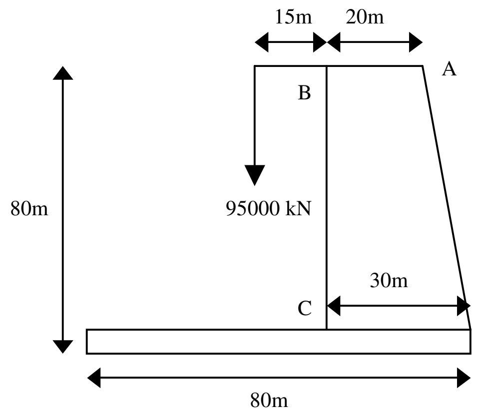

Figure 6: 'Svanen' crane dimensions

The simplified model in Fig. 6 does not take account of any of the cross bracing and only considers two dimensions but still gives an idea of the loads.

We firstly consider the vertical member in compression. By taking moments about A, we can calculate the compressive force in the member.

$$\begin{gathered}(95000 \times 35) - (C \times 20) = 0. \\ C = 166250\ kN.\end{gathered} \tag{1}$$

It goes without saying that the force calculated in Eq. (1) is huge. The way in which the cross bracing is acting can now been understood. From Fig. 3 we can see that the bracing serves to shorten the effective length of the vertical member, giving it a far higher compressive capacity.

By taking moments about B we can find the tensile force in the slanted member.

$$\begin{gathered}(95000 \times 15) - (T \times 20) = 0. \\ T = 71250\ kN.\end{gathered} \tag{2}$$

As the member is slanted the actual tension in it will be as calculated in Eq. (3).

$$71250 \div \cos 7.1^o = 71801\ kN \tag{3}$$

A combination of the steel members of the crane carrying tension in a more efficient way and the tension force being smaller than the compression mean that the slanted members can be more slender than the compression members.

The critical moment found in the crane will be at its base, where the compression member joins the hull. Calculation of this moment is carried out in Eq. (4).

$$71250 \times 30 = 2137500\ kNm \tag{4}$$

This moment has to be counteracted by the buoyancy of the hulls protruding from underneath the crane. This prevents the crane from overturning and is aided by any dead load acting to the right of pivot point C, in Fig. 6. This is why the majority of the ships bulk is beneath the crane.

5.4 Construction of the Main Span

The main span of the bridge was constructed in four sections, supported on temporary piers, almost like a propped cantilever

Firstly, the truss spanning a quarter of the main span from the pier is placed and supported at its free end by a temporary support. The use of a temporary support is not always preferred in bridge construction due to the high cost of manufacture of both the support and multiple foundations, all of which will become redundant once the bridge is finished. However, the conditions in the Oresund waters lent themselves to this form of construction. The waters are shallow and ground conditions good allowing relatively cheap foundations.

Figure 7: Half of main span with temporary pier

The cables can then be fixed to this section of the bridge, ensuring it is supported. At the same time the pylon must be back stayed onto the approach bridge behind with a similar arrangement of cables to remove any significant bending moments in it. This is what allows the pylons to be relatively slim.

The temporary support can then be removed and placed at the centre of the main span, acting as support for both of the central sections of the truss. Fig. 7 shows clearly how the temporary support has been moved away from supporting the span as the stay-cables are attached. We can also see how the temporary support is wide enough to hold both centre spans of deck.

The next section of deck can then be placed and the cables attached in a similar fashion along with the back stay-cables. The other half of the main span was constructed using the same method.

5.5 Insitu welding of trusses

Welding on a construction site is not often seen as desirable as there can be several disadvantages such as expense, quality and time. However, in the case of the Oresund Bridge the prefabricated steel trusses had to be joined insitu. These welds are crucial to the bridges structural integrity as, obviously the bridge must be joined over the piers, and it is also important that the bridge function with the loss of one of the approach piers (if, for example, a ship collided with it).

The solution to providing a suitable environment in which to weld and therefore improve the quality of the weld and strength of the bridge was to enclose the areas being welding with temporary 'cabins' as shown in Fig. 8.

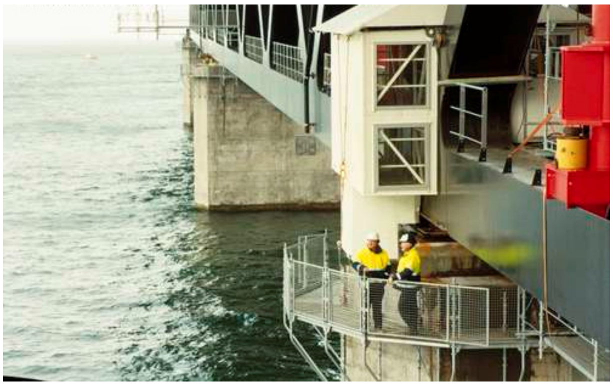

Figure 8: Enclosed welding cabins

These temporary cabins not only provided an environment similar to a workshop but also allowed work to continue regardless of the weather. This all contributed to being able to bring the project in on time.

5.6 Bearings

In Ref. [3] descriptions of the loads that the bearings are subjected to are given. The mageba pot bearings allow movement between the deck and piers and can carry vertical loads of up to 90,000 kN. In terms of horizontal forces the bearings are capable of carrying loads of 40,000 kN between the two bearings on each pier. This load would occur in the event of a ship collision.

5.7 Different Possible Construction Approaches

The issues with the construction of this bridge seem to revolve around the need to provide a split-level for road and rail traffic. If these could be placed on the same level an altogether different approach could have been adopted in both the design and construction of this bridge.

Had the road and rail traffic been on the same level and separated by a barrier of some sort the bridge deck would have most likely been made from concrete. This would of opened up several different possibilities in terms of construction methods, each with their advantages and disadvantages compared with the method used.

One method of bridge construction is the segmental cantilever approach. Using temporary cable-stays can reduce hogging moments over the piers, creating suspended cantilever construction. It is usual with cable-stayed bridge construction to use a suspended cantilever method, post-tensioning the segments back to the previous ones. This is part of the reason why cable stayed bridges constructed in this manor are so cost effective, as the temporary cable-stays become permanent. If the bridge had been carrying only road traffic it is likely it would have been made from concrete. This would have made construction of the bridge cheaper.

If we put aside the difficulties of splitting the road and rail traffic we can still see the advantage of using a truss in the bridges construction. The railway will require a far stiffer deck than a simple road bridge would, and so using a truss does not just serve to give a split deck but also gives a stiff deck which will move far less than a concrete deck.

6 Durability

The Oresund Bridge, as with a lot of new bridges, was designed for a 100-year life span. In order to generate the revenue to pay for itself the bridge has a toll and is expected to pay for itself within the next 20 to 30 years.

6.1 Corrosion

From Ref [4] it was recognised that the element of the bridge most susceptible to corrosion was the truss girders. The client asked that the same corrosion protection used on the girders should be able to be applied to all external steel work.

The specification used on the steel elements of the bridge is conventional in its make up, however it has been optimised to produce the maximum possible thickness of barrier coat over a primer that is sensitive to the thickness of the top coats.

Table 1: Coating specification

Coating	Material	Thickness
Primer	Zinc Rich Epoxy	40mm
Barrier 1	Epoxy Micaceous Iron Oxide	150mm
Barrier 2		150mm
Finish	Polyurethane	50mm

In order to further decrease the susceptibility of the steel work to corrosion, the Contractor's steelwork designs were reviewed at Arups. They were modified to reduce the possibility of water retention on areas of the structure. This included ensuring free run-off of water at node points and highlighting fabrication details that could act as water traps.

The bearings used on the Oresund Bridge were partly chosen for their durability in an aggressive ocean environment and have a design life of 30 years.

6.2 Replacement of cables

Compared with any suspension bridge the replacement of cables on cable-stayed bridges is far easier. As long as the bridge is designed to function safely with the removal of one of its cables it is just a process of taking one off and replacing it. This is complicated by pre-stressing requirements and traffic flow across the bridge, but is still far simpler than cable replacement on a suspension bridge.

7 Susceptibility to Damage

7.1 Unintentional

As with most bridges that cross a significant stretch of water the greatest unintentional threat to their structural integrity will come from a ship colliding with one of its piers, although this is unlikely. The way in which the Oresund Bridge has been designed has several advantages if it were to be hit by a ship. The leaf piers of the approach spans work in the same way as they do in highway bridges. The direction of collision is likely to results in high forces perpendicular to the bridge. A leaf pier is obviously stronger in this direction than two square piers would be. In a worst-case scenario the bridge engineers should have designed it to be serviceable if it loses one of its piers completely. The welds between the trusses over each pier should act to make the trusses continuous over the piers. This should mean that, were a pier to be taken away the trusses could span twice the distance.

The main span piers are not leaf piers and so will not have as higher collision capacity as the approach piers, although they do carry a higher compressive force, which increases their moment capacity. To give these pylons some protection they have artificial islands built at their bases. These are just below the level of the water and will slow or prevent any ships that would otherwise collide with a pier.

7.2 Intentional

As with any large structure in an age where terrorism is becoming more frequent the Oresund Bridge has the very small possibility of being targeted. However, looking at the current political climate in Sweden, Denmark and the Oresund Region the likelihood of such an attack is relatively small.

8 Loadings

8.1 Dead Load

The Oresund Bridges deck is made of steel trusses. This allows the road and rail traffic to be separated onto upper and lower parts of the deck. As the deck is steel it is perhaps lighter than would be expected from a concrete deck. It will also be stiffer than a conventional post-tensioned concrete deck, due to the need to carry rail traffic. Added dead load will come from the casting of the concrete deck on top of the girders, along with any other superimposed dead loads such as services, lighting and blacktop.

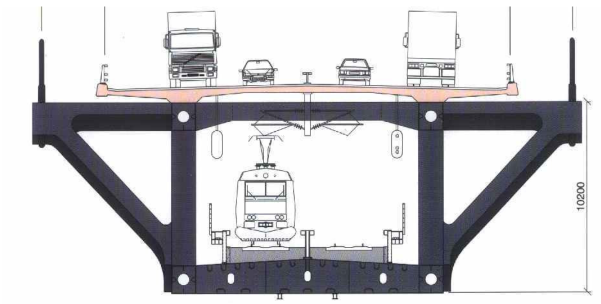

Figure 9: Oresund bridge deck section

The train line, which runs on the lower part of the deck, sits in a concrete trough over the approach bridges. When the trough reaches the main span bridge it changes to steel. This reduces the load on the main span and could perhaps allow more flexibility as the main span may well move more than the approach spans.

The weight of the deck and truss combined when lifted into place was approximately 43 tonnes per metre length.

8.2 Live Load

The Oresund Bridge carries both road traffic and rail traffic. The bridge carries four lanes of traffic (two in each direction). The rail traffic is carried beneath the carriageways giving the bridge its trussed form. It is sensible to separate out the two forms of transport in this manor as it gives the maximum amount of protection in the event of any accidents. It would have been possible to carry both rail and road traffic on the same level of the bridge. This would allow the deck to be less deep in section and perhaps improve the aesthetics of the bridge, allowing the pylons to become the main structural element rather than the deck. The problem with this is how to prevent vehicles breaching the rail track and vice versa. This could be done with substantial concrete barriers however this would perhaps make people feel a little enclosed whilst driving over the bridge and add extra material and load to the bridge.

As the bridge is required to carry rail traffic the bridges deck needs to be stiffer than usual. The use of a truss makes sense for the Oresund Bridge as, although the bridge could be improved aesthetically by using a thinner deck, it provides increase rigidity and also the necessary separation of the two modes of transport. However, the use of a truss increases the loading on the bridge due to wind.

8.3 Temperature

For the case of loading through temperature changes, we can firstly consider the overall lengthening and contracting of the bridge. Assuming that the range of temperatures in the Oresund Region could be between –10°C and 30°C giving a range of 40°C and that the overall length of the bridge is 7845m, the movement of the deck will be as follows.

$$\begin{aligned} \Delta L &= \Delta T \text{ x } L \text{ x } \alpha \\ \Delta L &= 40 \text{ x } 7845000 \text{ x } 12\text{x}10^{-6} \\ \Delta L &= 3766 \ mm \end{aligned} \tag{5}$$

The value calculated in Eq. (5) is huge as it is for the entire length of the bridge. However, this change in length either has to be taken at one or two expansion joints or at several more smaller expansion joints across the bridge. Were the change in length not taken by the expansion joints the apparent compressive forces created would be huge, as calculated in Eq. (6).

$$\begin{aligned} \sigma_c &= \varepsilon \text{ x } E \\ \sigma_c &= 480\text{x}10^{-6} \text{ x } 200000 \\ \sigma_c &= 96 \ N/mm^2 \end{aligned} \tag{6}$$

This force is definitely too high for the bridge to take and would certainly lead to a collapse.

The second form of temperature loading to consider is the variation in temperature between the top and bottom of the deck. This can be calculated using various tables and graphs from BS 5400, and is shown below.

The difference in temperature between the topside and underside of the deck could be approximated to about 16°C. The strain and corresponding moments and axial loads can then be calculated as below.

$$\varepsilon_{max} = \Delta T \text{ x } \alpha = 16 \text{ x } 12\text{x}10^{-6} = 192 \ \mu\varepsilon \tag{7}$$

$$\sigma_{max} = \varepsilon_{max} \text{ x } E = 192\text{x}10^{-6} \text{ x } 200000 = 38.4 \ N/mm^2 \tag{8}$$

In order to calculate the axial load and bending moment caused by this difference in temperature we will need to know where the centroidal axis of the deck cross-section lies. In the Oresund Bridge this is at a depth of about 0.35d. Using linear interpolation we can now find the stress and this depth.

$$(38.4 \div \text{d}) \text{ x } 0.65\text{d} = \sigma_{axial} = 25 \text{ N/mm}^2 \tag{9}$$

8.4 Wind

Another of the major factors affecting this bridge will be the wind loading. The wind will act in two ways on the bridge. The first being horizontally on the side of the bridge the second longitudinally causing uplift or a downward force.

Assuming that the mean hourly wind speed is approximately 30ms^{-1} and the wind coefficient, K_1, and hourly speed factor, S_2, for the Oresund Bridge are 1.60 and 1.36 respectively, the maximum wind gust, v_c, is as follows.

$$\begin{aligned} v_c &= v \text{ x } K_1 \text{ x } S_2 \\ v_c &= 65.28 \ ms^{-1} \end{aligned} \tag{10}$$

For the trussed deck of the Oresund Bridge, the solidity ratio will be approximately 0.3. This gives a drag coefficient, C_D, of 1.7. As the side of the Oresund Bridge is approximately 6m in depth and the main span is 490m we can calculate A_1. The horizontal force resisted by the bearings on the main span is calculated in Eq. (11).

$$\begin{aligned} P_t &= q \text{ x } A_1 \text{ x } C_D \\ P_t &= (0.613 \text{ x } 65.28^2) \text{ x } (0.3 \text{ x } 6 \text{ x } 245) \text{ x } 1.7 \\ P_t &= 1959 \ kN \end{aligned} \tag{11}$$

A similar calculation can be carried out to find the wind loading on the piers. As the designer of the bridge has chosen not to join the piers at the top this loading would have been the critical to calculate moments at the piers bases and check they were capable of resisting them. The Oresund's piers are square and 203m in height. Given that they are 6m wide this gives a drag coefficient, C_D , of approximately 2.0. Using Eq. (11) again we can find the load on the pier.

$$\begin{aligned} P_t &= (0.613 \text{ x } 65.28^2) \text{ x } (6 \text{ x } 203) \text{ x } 2.0 \\ P_t &= 6364 \ kN \end{aligned} \tag{12}$$

This load can be translated into a bending moment about the base of the pier of 645946 kNm. The piers will of course be partially restrained where the deck passes between them, however this will not reduce the moment about the base drastically. The foundations become more expensive as the forces they must resist increase and so maybe the size of the foundations could have been reduced if the piers were connected at their tops.

In order to calculate the uplift or vertical downward forced caused by the wind we use a similar equation to that used in Eq. (7).

Assuming that the bridge has a deck width of 20m and depth of 6m, C_L can be found to be 0.4. The vertical force on the bridge can then be calculated, Eq. (13).

$$P_t = q \text{ x } A_3 \text{ x } C_L$$
$$P_t = (0.613 \text{ x } 65.28^2) \text{ x } (20 \text{ x } 245) \text{ x } 0.4 \quad (13)$$
$$P_t = 5120 \text{ kN}$$

The value generated in Eq. (13) gives an idea of the pre-stressing that would have been required in the cable-stays of the Oresund Bridge. This pre-stress is required to prevent the cables from becoming slack if the bridge were to lift in the wind. If the main span cables did become slack the deck would begin to vibrate and this would have severe consequences in terms of the bridges serviceability and structural safety.

8.5 Loading Combinations used in analysis

In order to carry out a numerical analysis of the Oresund Bridge I will consider only one of the different loading combinations in order to give worst-case results on individual elements of the bridge. In practice all five of the loading combinations would be checked.

To give the maximum forces in the cables and therefore the maximum compressive load in the piers I will use a combination of all the permanent loads, any primary live loads and downward wind load. This will also give the maximum load in the stay cables and any associated tensile forces in the piers below the stay-cables.

9 Numerical Analysis of the Oresund Bridge

To give a better impression of how the Oresund Bridge works structurally it is important to show some of the forces and moments applied to it. The cable-stayed design means it is important that the cables either side of the pylon remain approximately in equilibrium. This reduces the moment in the pylon and allows it to be slender.

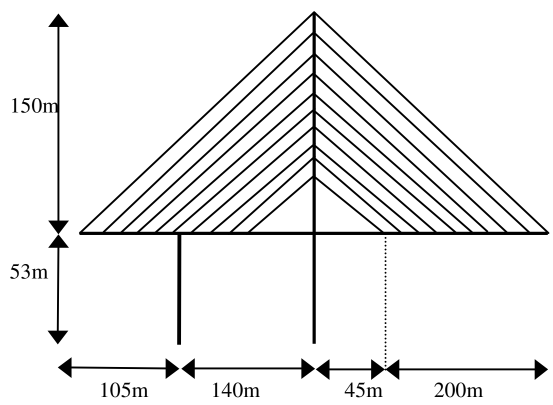

Figure 10: Simplified bridge model

Firstly, I have put some numbers to the bridge to show approximate tensions in cables and compressions in the pylons and deck. In order to simplify I have considered only one plane of cables and so halved the load.

In order to calculate the highest forces in the cables, deck and pylons I will use the loading discussed in 7.5, consisting of the permanent loads along with the downward wind load calculated in Eq. (13). For this load combination the corresponding load factors, γ_{fl} and γ_{f3}, are both 1.1. Assuming that the deck weighs approximately 43 tonnes per meter, the loading per meter of bridge can then be found as below in Eq. (14).

$$(245 \text{ x } 430) + 5120 = 110470 \text{ kN}$$
$$110470 \text{ x } 1.1 \text{ x } 1.1 = 133669 \text{ kN} \quad (14)$$
$$UDL = (133699 \div 2) \div 245 = 273 \text{ kN/m}$$

The cables will each support a segment 10m in length except for the cable lowest down the pylon, which will support a segment 22.5m in length. The angle between the cable and horizontal is approximately 32°. The tensions in the cables are calculated in Eq. (15) for the 10m segments and Eq. (16) for the 22.5m segments.

$$(10 \text{ x } 273) \div \sin 32^o = 5152 \text{ kN} \quad (15)$$

$$(22.5 \text{ x } 273) \div \sin 32^o = 11592 \text{ kN} \quad (16)$$

From the value calculated in Eq. (16) we can estimate the diameter of cable required to carry this load. Assuming the strength of the cable is 1700 N/mm^2 and is pre-stressed to 50% of its capacity, the diameter of cable is shown in Eq. (17).

$$A \text{ x } (1700 \text{ x } 0.5) = 11592 \text{x} 10^3$$
$$r^2\pi = (11592 \text{x} 10^3) \div 750 \quad (17)$$
$$d = 140 \text{mm}$$

As the stay cables are inclined they cause a resultant compressive force in the deck. This compressive force increases as you move towards the pylon and is at its greatest directly beneath the pylons.

$$(546 \text{ x } 10) \div \tan 32^o = 8738 \text{ kN}$$
$$(546 \text{ x } 22.5) \div \tan 32^o = 19660 \text{ kN} \quad (18)$$
$$C = (8738 \text{ x } 9) + 19660 = 98302 \text{ kN}$$

The compressive force calculated in Eq. (18) is large but the trussed design of the bridge means it is easily capable of carrying this force. The compressive force is giving the deck more rigidity, which is ideal for bridges carrying rail traffic.

The tensile forces in the cables will be translated to compressive forces in the pylons. The structural system as a whole is shown in Fig. 11.

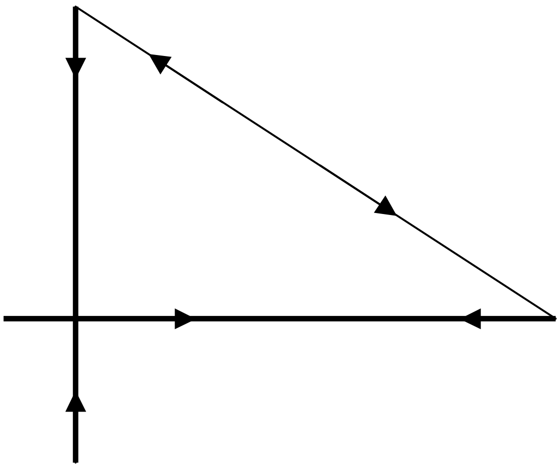

Figure 11: Triangle of forces in bridge

The compressive forces in the pylons can be calculated in a similar way to the compressive forces in the deck. The compressive load in the pylon will be affected by its own self-weight, but if we consider the load from the cable stays only we can calculate the compressive load, shown in Eq. (19).

$$\begin{gathered} 5152 \times \sin 32^o = 2730\ kN \\ 11592 \times \sin 32^o = 6143\ kN \\ C = (9 \times 2730) + 6143 = 30713\ kN \end{gathered} \tag{19}$$

This compressive force in the pylons will give it a higher moment capacity.

As with any cable-stayed bridge, the back stays need to remain in tension and so it is important that the deck does not rise in the wind as this will loosen the cables and allow the main span to drop. This could well be the function of the pier placed underneath the back-stayed portion of the bridge. When the wind load applies uplift to the back-stayed portion of the bridge the pier acts as a tie in order to prevent the deck from lifting and slackening the back stay-cables.

10 The future of the Oresund Bridge

As with many roads and bridges around the world the traffic frequency across the Oresund is set to increase. Ref [5] shows there was a 17% increase in traffic experienced in the first 6 months after the bridges opening. This may well be a skewed statistic as the traffic flow in the first months of the bridge is bound to increase. However, if traffic continues to increase at even a small amount of this 17% per 6 months the two lane of traffic in each direction will probably be at capacity within decades.

Assuming that the Oresund Bridge did require widening there would be a couple of obvious options. As you can see from Fig. 9 the carriageway does not reach to the edge of the truss. It would be possible to cast a wider deck element with the possibility of adding an extra lane in either direction. This would bring the carriageway closer to the edge of the bridge and add a significant amount of dead load to the structure.

Another option would be to hang new truss elements off the side of the existing deck. This would seem to be a more complex procedure than the first one suggested, but could add more than one lane in either direction.

All of these modifications would have effects on the loading of the bridge and strengthening works could well be required for both the cables and the piers.

References

[1] BYTEachers 2002, *The Oresund Bridge [online]*
Available at:
www.spartacus.schoolnet.co.uk/TVSmalmo.htm
[Accessed 19th April 2007]

[2] Financial Times 2000, *Oresund Bridge: A link to establish economic zone [online]*
Available at:
www.specials.ft.com/ln/ftsurveys/country/scb102.htm
[Accessed 19th April 2007]

[3] Mageba 2000, *Oresund Bridge bearings [online]*
Available at:
www.mageba.ch/en/dyn_output.html?content.void=700&SID=498a3257d4db93eb5e9ee9d209b8da77
[Accessed 19th April 2007]

[4] Nissen, J. and Falbe-Hansen, K., 2000, The Oresund Bridge completion, *The Arup Journal 3/2000*

[5] Oresundsbron 2004, *Oresund Bridge History [online]*
Available at:
www.osb.oeresundsbron.dk/documents/document.php?obj=1009
[Accessed 19th April 2007]