Efficient Utilisation of Optimal Network Arches

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ABSTRACT: Network arches have inclined hangers that cross each other at least twice. When the distance between the planes of the arches is less than 15m, the tie should be a concrete slab with moderate longitudinal prestress. The bending moments in the longitudinal direction are usually smaller than the bending moments in the middle of the slab.

For load cases which cause no hangers or only a few hangers to relax, network arches act very much like many trusses on top of each other. The buckling stress of the arch is high. Tension is predominant in the rest of the structure. Thus the network arch makes good use of high strength steels.

The slim network arches look attractive. Efficient methods of erection are available. The details are simple and repetitive. The exposed surface is small. An optimal network arch can normally save ⅔ of the steel compared to other steel bridges. Where many equal spans are needed over navigable water, all concrete network arches can be made on land to be lifted in place by big floating cranes.

1.1. Slim network arches

Fig. 1. Bolstadstraumen Bridge in western Norway.

The author’s first network arch was built at Steinkjer. Bolstadstraumen Bridge, was the author’s second network arch and has a span of 84m. Both of these network arches were finished in 1963 and both were built in Norway. (Tveit 2008) p.7 and 7a.

The rise of the arch was 18 % of the span. To save steel, a competing arch bridge with vertical hangers had a rise of 21.5% of the span. However, it needed 2.5 times more structural steel. Both bridges had a concrete slab between the planes of the arches.

We can define the slenderness of an arch bridge as the span divided by the sum of the height of the chords. By this definition the Bolstadstraumen Bridge has a slenderness of 91. It was the world’s most slender tied arch bridge up to 2008.

Then the Mangamahu Bridge in fig. 2 was built in New Zealand in 2008. (Chan & Romanes 2008). It has a span of 85 m and is 4 % slimmer than the Bolstadstraumen Bridge.

Fig. 2. Mangamahu Bridge, New Zealand.

2.1 General features of network arches

In network arches some hangers cross other hangers at least twice. The network arch functions as a combination of a tied arch and a truss. As long as all hangers are in tension, it normally has less bending than a truss.

The network arch can be seen as a beam with a compression and a tension zone. An increase in the rise of the arch will give smaller axial forces in the chords and lower steel weight. It is mainly aesthetic considerations that limit the rise of the arches.

Most of the shear force is taken by the vertical component of the arch force. The hangers act like a light web. They take some of the variation in the shear force. All members in a network arch efficiently carry the forces that can not be avoided in any simply supported beam. The tie is best made of concrete with longitudinal prestressing cables.

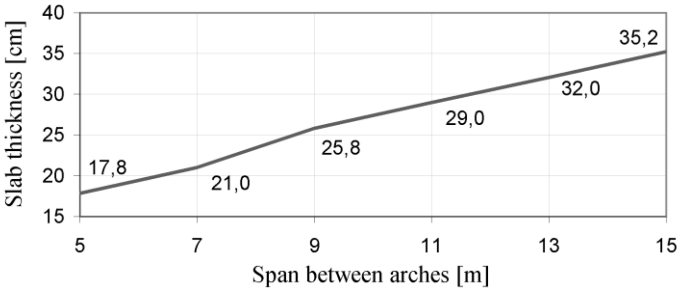


Fig. 3. Slab thickness in network arches. C 40/50

Fig. 3 shows the thickness needed to get enough strength in the concrete slabs between arches. (Teich & Wendelin 2001). The transverse bending moment in the slab tie is usually much greater than the longitudinal bending moment. (Tveit 2008) p. 14.

The main purpose of the edge beam is to accommodate the hanger forces and the longitudinal prestressing cables. The use of a partial longitudinal prestress in the tie reduces the cracks. This is part of the reason why the two Norwegian network arches are in good shape after 46 years. (Tveit 2007)

When the arches are between 10 and 15 m apart, a transverse prestress in the slab between the planes of the arches should be considered.

For spans up to 150m the author would normally recommend the use of arches made from universal columns or American wide flange beams. The main advantages of these profiles are smaller amounts of welding, smaller dimensions and simpler details. The arch is likely to have an equal tendency to buckle in and out of the plane of the arch. (Tveit 2008) p. 25.

For load cases that relax none or only a few hangers, network arches have little bending in the chords. To avoid extensive relaxation of hangers, the hangers should not be inclined too steeply. Small inclination of hangers tends to increase the bending moments due to concentrated loads. A compromise should be sought. All hangers might have the same cross-section and nearly the same decisive load. Their upper nodes should normally be placed equidistantly along the arch.

Because there is little slenderness in the arch, and tension is predominant in the rest of a network arch, this type of bridge makes good use of high strength steels.

Network arches are very stiff. This is very important when the network arch is used for railway bridges, especially in bridges for high speed railways.

Compared to conventional tied arch bridges, network arches without steel beams in the tie usually saves ⅔ of the structural steel. If there are steel beams in the tie, ⅓ of the steel weight is likely to be saved.

3.1 *Optimal network arches compared to other steel bridges*

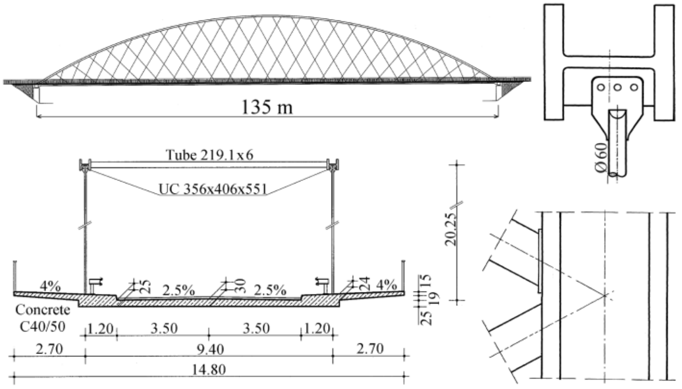


Fig. 4. The Åkviksound network arch designed in 2001

Two very able students of Professor W. Graße in TU-Dresden wrote their graduation thesis in Norway in the summer of 2001. (Teich and Wendelin 2001). They calculated the optimal network arch in fig. 4. The resulting steel weights per m^2 of useful bridge area are shown on the left in fig. 5.

The loads and codes of the EU were used. Where there was doubt, solutions that gave the bigger steel weight were adopted. A revised version of the students' graduation thesis can be found at http://fag.grm.hia.no/fagstoff/ptveit/

Fig. 5 compares the steel weight of the network arch in fig. 4 to steel weights in recent German arch bridges with vertical hangers. The year that the bridges were built is indicated. Bridges marked N have no wind bracing. In bridges marked S the arches slope towards each other.

The network arch tends to use less reinforcement in the concrete tie than the bridges that have steel beams under the concrete slab. Part of the reason for this is the high amount of minimum reinforcement that is needed in the slab that lies on top of the elongating longitudinal steel beams in the tie.

In the optimal network arch the moderate longitudinal prestress in the serviceable limit state reduces the need for minimum reinforcement.

When the concrete slab can carry the concentrated load, small amounts of extra reinforcement are needed to take the load to the edge beams.

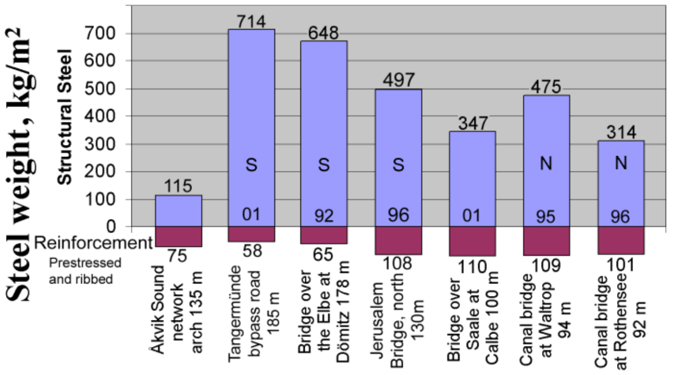


Fig. 5. Steel weight per square metre for various arch bridges

The Jerusalem Bridge in Magdeburg uses more than 4 times as much structural steel per m^2 as the Åkvik Sound Bridge. The spans are nearly the same. The Åkvik Sound Bridge comes out better partly because the area under the arches is included in the surface that is used for calculating the steel weight in kg/m^2.

Different methods of erection contribute to the great variation in steel weight in fig. 5. A temporary tie for the Åkvik Sound network arch would need a steel weight of ~45 kg/m^2.

In the Åkvik Sound network arch pre-bent H-profiles made of S 460 are assumed. In 2003 a steel mill said that these profiles would cost between 22% and 30% more than straight profiles in grade S 355.

Steel weight is not the only thing that matters. The table in fig. 6 indicates other things that might be important. It seems that network arches might cost less per ton than the steel in arch bridges with vertical hangers.

References containing the steel weights of bridges can be found in [Tveit 2002] and [Herzog 1975]. They say that arches bridges use about the same amount of steel as other steel bridges. This indicates that network arches use much less steel than other road and rail bridges.

POINTS OF IMPORTANCE	OTHER STEEL BRIDGES COMPARED TO OPTIMAL NETWORK ARCHES
Aesthetics	Bulkier bridges
Adaptability	2 to 8 times deeper lower chords
Materials	2 to 4 times the steel weight
Fabrication	15 to 30 times longer welds More complicated details
Corrosion protection	3 to 7 times more surface to protect.
Maintenance	Concrete parts need much more maintenance than concrete slabs with a slight prestress
Erection • Floating into place • Erection on ramps • Erection on ice	2 to 4 times more steel makes erection more expensive.

Fig. 6 compares other steel bridges to optimal network arches

3.2 Saving in cost by using network arches instead of other tied arch steel bridges

In his work with network arches the author has presented influence lines and quantities to make it easy for fellow engineers to check his claims concerning savings of materials. (Tveit 2008) p. 39, 57, 58, 60, 72, 78-86.

The author has been reluctant to specify savings in US dollars or sterling because such savings are much more difficult to defend.

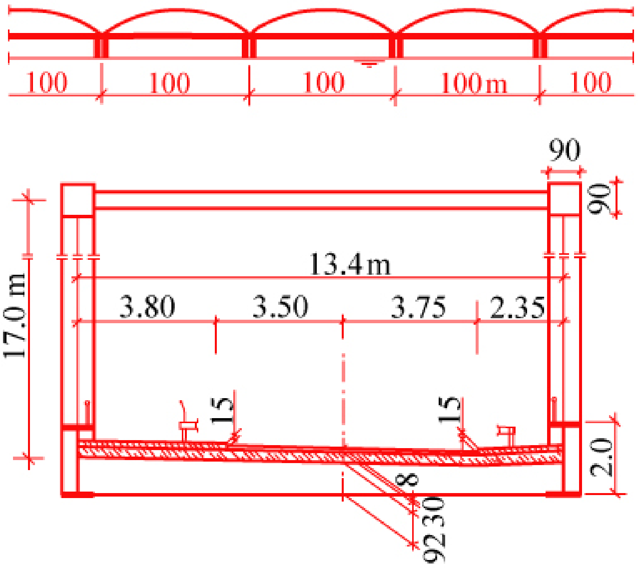
The reduction in cost resulting from the use of network arch bridges is of great interest. Therefore a network arch with a span of 150 m is compared to an arch bridge with vertical hangers spanning 100 m built over the river Saale near Calbe in Germany, (Fiedler and Ziemann 1997). See fig. 7.

At similar sites network arches should normally have longer spans than other bridge types, because the steel weight of the network arch is smaller and it increases more slowly with increasing spans. This is an extra advantage for the network arch when the size of the pillars depends mainly on the forces due to collision with ship. p. 93a to 93c.

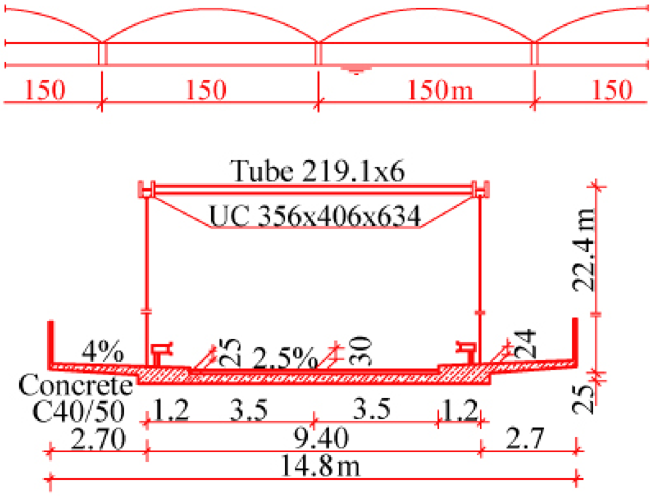
Material and cost of the Calbe Bridge compared to that of a network arch

Comparison of weight per m^2 of useful bridge area

Main span over Saale at Cable



Network arch



58 % of the structural steel is saved
34 % of the reinforcement is saved
24 % of the concrete is saved

The pillars are the same for both bridges
Less weight needs to be moved during erection

The saving in cost is probably 35 to 45% per m^2 of useful bridge area

Fig. 7. Comparison of cost of two bridges

The data for the network arch in fig. 7 are based on the network arch designed by Teich and Wendelin 2001.

The cost per m^2 of bridge between the railings is compared. The average width between the railings is 13.9 m for the Calbe Bridge and 14.8 m for the network arch. Both bridges are assumed to have many equal spans.

Factors that influence the cost of the two spans are presented in Tveit 2008. p. 93a to 93c. It is shown that the network arch with a span of 150 m will need about the same size of supports as the 100 m arch bridge with vertical hangers. The loads and codes of the EU are used for both spans.

4.1 Arrangement of hangers

If the hangers cross each other many times, most of the advantages of network arches are obtained, but still more savings can be achieved. It looks good if the distance between nodal points in the arch is constant, but the distance from the end of the arch to the first node should be about 50 % longer.

In the two Norwegian network arches nearly parallel hangers next to each other had a constant difference in slope. The steepest hanger sloped towards the middle of the bridge. See (Tveit 2008) p. 57 and 58.

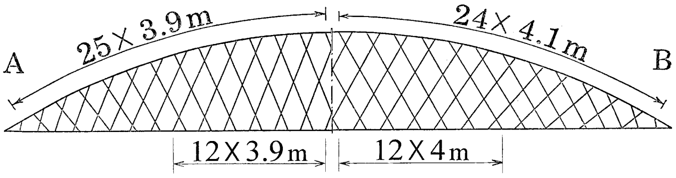


Fig 8. Arrangement of hangers for two bridges spanning 200 m

For the IABSE conference in Vienna in 1980 the author presented the two hanger arrangements shown in fig. 8. They were found by trial and error. In order to reduce the longitudinal bending moments in the edge beam, there is a constant distance between the nodes in the middle of the tie.

The coordinates can be found in (Tveit 1980) p. 62 and 76. The arrangement to the right has been used in the bridge in fig. 4.

In their master's thesis (Brunn & Schanack 2003) suggested that there should be a constant angle between arch and hangers. This is a good idea.

In his unfinished doctoral thesis Stephan Teich found that Brunn and Schanack's and the hanger arrangement in the two first Norwegian network arches were the best ones of those examined.

Near the ends of arches it is best to vary the angle between the hangers. The optimal variation is dependent on the stiffness of the chords, the ratio between live and dead load and the variation in the live load.

A bridge that carries a lot of traffic must avoid fatigue in the hangers. Then the force in the hangers should not vary too much. This usually leads to bridges with hanger arrangements that give no relaxation of hangers. This is convenient because relaxing of hangers decrease the buckling strength in the arch.

5.1 Erection of network arches

The economy of a network arch depends of finding an efficient method of erection.

The first two Norwegian network arches were built on timber structures on piles in the river bed. After the concrete tie had been cast, it provided a good platform for erecting the arch and the hangers. Then the hangers were tightened till they carried the tie and the timber structure could be removed.

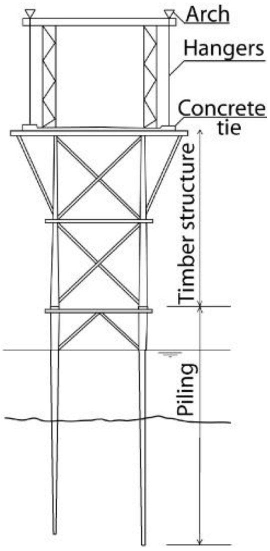
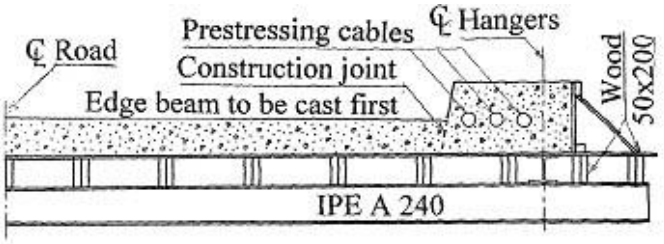
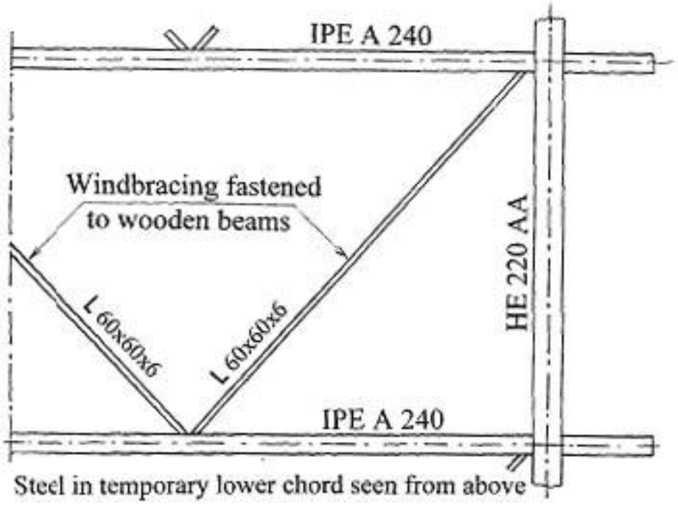


Fig. 9. Erection of the bridge in fig. 1

Fig. 10 shows a temporary tie of a network arch with a concrete tie. Combined with arches and hangers it makes a stiff steel skeleton that can be moved. The steel skeleton can carry the casting of the concrete tie.



Cross-section of formwork and half the permanent and temporary lower chord. (Camber of the transversal beams is not shown)



Steel in temporary lower chord seen from above

Fig. 10. A temporary tie for a network arch

First the concrete is cast around the curved parts of the prestressing cables at the ends of the tie. After that a slight prestress can reduce the stress in the beams at the ends of the tie. Then the edge beams are cast.

The casting must be done from both sides of the spans to avoid relaxations that can lead to big deflections. Now the bending is taken mainly by the edge beam. Then the concrete slab is cast.

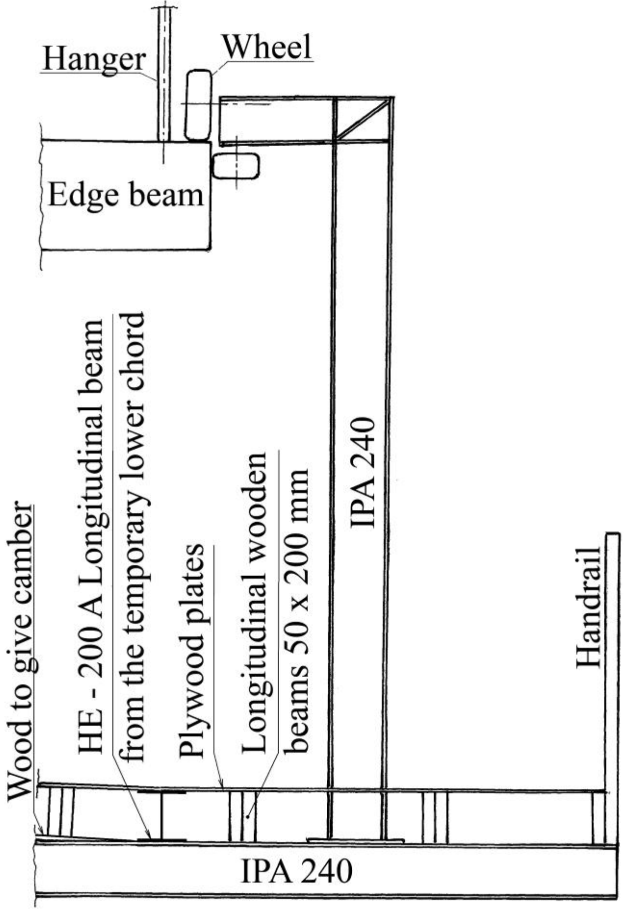


Fig. 11. A wagon for removing a temporary tie

Fig. 11 shows the cross-section of a wagon for removing the formwork and the temporary tie of a network arch. It rolls along the edge of the finished tie. (Tveit 2008) p. 52 and 53.

The floor in the removal wagon has been part of the formwork for the casting of the tie. It has been lowered after the casting was finished. The longitudinal beam from the temporary lower chord can be seen in fig. 11.

Fig. 12 shows an early stage in the erection of a skewed bridge across a canal. The span is 100 m. In order to reduce the thickness of the concrete tie three arches are used.

The structural steel, supplemented by a temporary lower chord, is erected on the ramps or the side spans. If the shape of the steel skeleton is right, then no adjustment of the steel skeleton is needed later.

While the beams on top of the pontoon are being tied to the abutment, the steel skeleton is rolled to the middle of the pontoon. Then the steel skeleton is rolled onto the abutment and the concrete is cast.

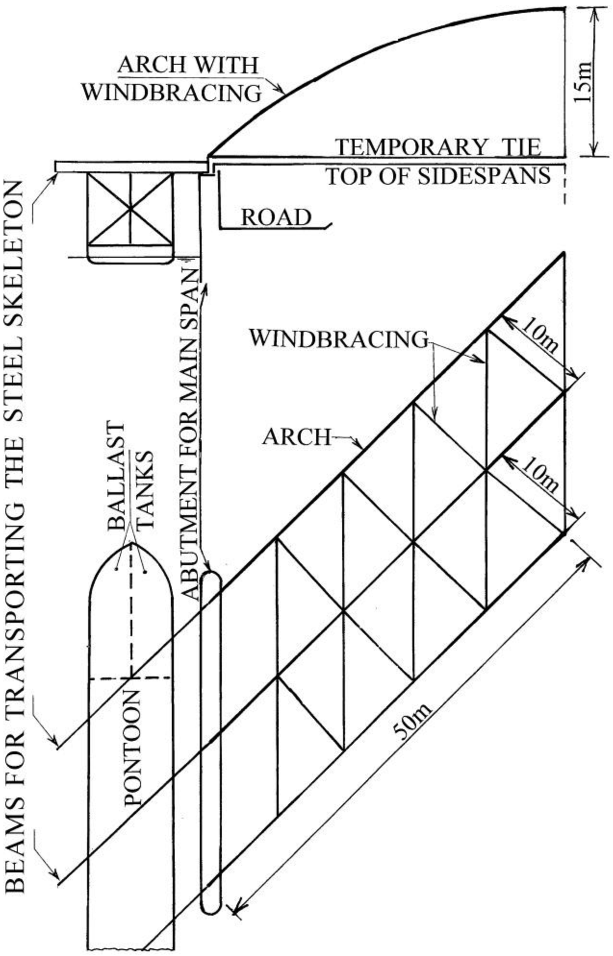


Fig. 12. A stage of the erection of a skew bridge across a canal

Fig. 13. Lifting the steel skeleton of the bridge in fig. 4

Fig. 13 shows the 135m 230 t steel skeleton of the bridge in fig. 4 lifted in place by Norway’s biggest floating crane. The lifting capacity is 600 t.

The limited room under the hooks normally decides how high the steel skeleton can be lifted. Normally one crane at each end of the span is better.

The bridge in fig. 4 can be finished on land to be lifted in place by two cranes lifting 900 t each. Stronger concrete would reduce this weight.

The steel skeleton of the 80 m span in fig. 2 was lifted in place by mobile cranes. Mobile cranes are likely to be used frequently for erection of or narrow network arches in the future.

5.1 Side spans for the Fehmarn Belt Bridge

Now the author will mention a bridge type that can be used in long bridges with many equal spans over navigable water. It is a high strength concrete network arch built on land and lifted in place by big floating cranes. It has not been built yet. See (Tveit 2008) p. 47 to 50.

Last year the author suggested such network arches for the 16 km of side spans for the Fehmarn Belt between Denmark and Germany. The cross-section in the middle of the suggested 250 m side spans are shown in fig. 14.

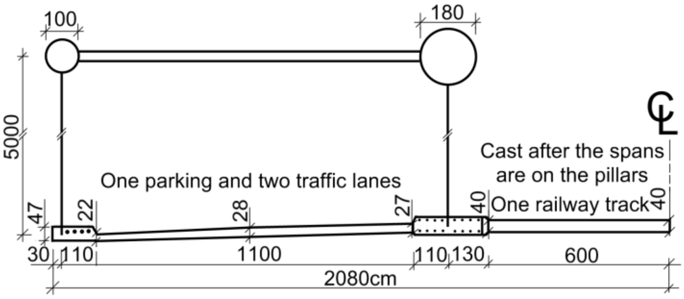


Fig. 14. Cross-section of an all concrete side span

Two arches with the road in one direction would weigh ~6600 t. They can be lifted out by two seagoing cranes. Such cranes exist. The concrete slab under the railway track can be cast when the four arches for the roads are in place.

The side spans can be made of concrete ~C80/95. Since there is little bending in the arch, it can be made of prefabricated elements like the one in fig. 15. The wind portal should be cast in situ.

The author presented his ideas to Design Manager Jørgen Gimsing of the Femarn Bælt A/S. He got a nice letter back stating that cost estimates were highly sensitive to the relative cost of steel and concrete.

Gimsing found the network arch to be 3 % less costly than the two level steel spans that will be used for the Femarn Bælt Bridge, but for many reasons he found the two level solution to be preferable.

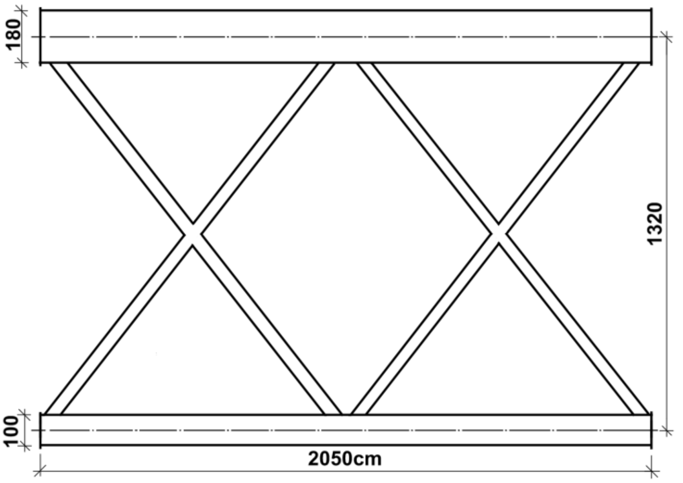


Fig. 15. Prefabricated part of arch seen from above

The author would like some clever students to come to him and do their master's thesis on the side spans of the Fehmarn Belt Bridge, because it is not the last bridge with many spans to be built over navigable water.

The students will be asked to calculate the side spans using an extensive computer program and check some central dimensions. Thus they will obtain a good general knowledge of network arches.

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