

This manuscript is a revised version of a lecture that IABSE has asked the author to put on the internet. You can look it up here: <http://www.elearning-iabse.org/120/>. Page numbers in *italics* refer to "The Network Arch". See home page: <http://home.uia.no/pert/index.php/Home>. A few of the page numbers might be altered in coming editions.

The author first used the expression "Network Arch" in (Tveit 66). It means an arch bridge with hangers that cross each other at least twice. When the tie is made of concrete, it uses less than half the steel needed for other steel bridges.

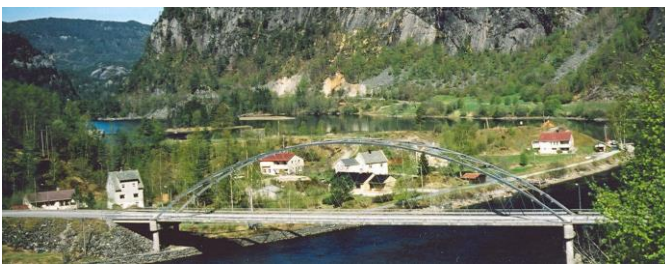


Fig. 1. Bolstadstrumen Bridge spans 84 m

The author's second network arch, Bolstadstraumen Bridge, is shown in Fig. 1. It was finished late in 1963. *Pp. 7 and 8*. The author wanted to design an economical bridge, otherwise he would not have been paid for his work.

The bridge needed 44 t of structural steel and 7 t of prestressing steel. It had a rise of the arch that was 18 % of the span. A competing arch bridge with vertical hangers and a rise of the arch of 21.5 % of the span needed 2.5 times more structural steel. Both bridges had a concrete slab between the arches.

If we define the slenderness of an arch bridge as the span divided by the sum of the height of the chords, the Bolstadstraumen Bridge was the world's most slender arch bridge for over 30 years.

Now the Brandanger Bridge is the worlds most slender arch bridge. See Tveit 2013 p.94 to p.94a.

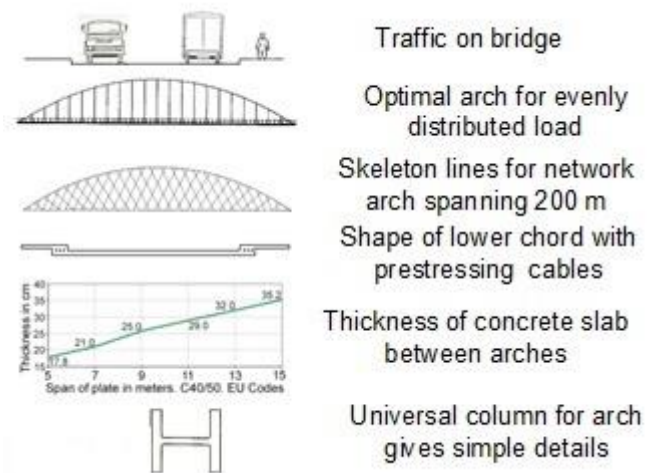


Fig. 2. Reasoning behind an efficient network arch

The purpose of a bridge is to take traffic over an obstacle. Often there is no room for members under the bridge. For an evenly distributed load an arch with vertical hangers is a very good solution. All the members can have mainly axial forces.

For uneven loads it is best to use crossing hangers like in the network arch. Then all loads are transferred to the arches in such a way that there is very little bending in the chords. The bending in the members is usually less than in trusses.

That applies if we do not use the usual assumption that there is a frictionless joint in every node in the truss. In the last hundred years the uneven load on bridges has increased much more than the evenly distributed loads, and the structural materials have become stronger. This speaks for the network arches.

The simplest tie would be a concrete slab spanning between the arches. The tensile force in the tie is best taken by prestressing cables in the edge beam. They give a beneficial compressive stress in the tie. This leads to less maintenance of the concrete tie. Since there is very little longitudinal bending in the tie, it can be very slim.

In fig. 2 the necessary thicknesses of a slab spanning between arches are indicated. For distances between the arches of between 12m and 18m transversal prestress should be considered, but it is usually not efficient.

The hangers give the arch good support in the plane of the arch. Universal columns or American wide flange beams can be used. They give very slender bridges. The universal columns in the arches should have a horizontal web. Then the buckling strength could be about the same in the plane of the arch and out of the plane of the arch.

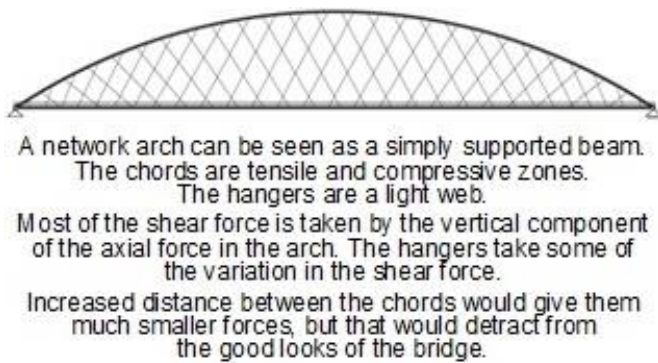


Fig. 3. Beam analogy

A network arch can be seen as a simply supported beam. The arch is the compression zone, and the tie is the tension zone. The hangers are the web. Most of the shear force is taken by the vertical component of the compressive force in the arch. Some of the variation in the shear force is taken by the hangers.

The force in the chords can be reduced by increasing the distance between them, but aesthetic considerations limit the rise of the arch. A rise of the arch 0.15 times the span usually looks best. This rise is frequently used in Germany. American network arches can have a rise of up to 0.2 times the span of the bridges. Most Japanese network arches lie in between.

In network arches some mainly axial forces can not be avoided. The optimal network arch takes these forces as efficiently as possible. The optimal network arch is an efficient structure for the following reasons:

The details are simple, light and highly repetitive. Tension is predominant in the hangers and in the tie. There is little bending in the chords. The arch gets good support from the hangers, and so there is little tendency for buckling in the plane of the arch. The buckling strength in the arch is high. All members make good use of high strength steels.

The hangers distribute the loads between the chords in such a way that there is very little bending in the chords, as long as all, or all but a few hangers are in tension. The hanger arrangement in fig. 3 gave no relaxation of hangers in the serviceability limit state. The hangers can be steel rods or wires. They should be checked for fatigue.

Now comes a list of characteristics of optimal network arches.

- Some of the hangers cross each other at least twice. The tie is a concrete slab.
- There is little bending in the chords
- Tension is predominant in the tie and hangers
- Compression is predominant in the arch
- The arch is well supported in the plane of the arch
- High strength steel is well utilized. There are longitudinal prestressing cables in the tie.

Fig. 4. Characteristics of an optimal network arch

By now the fundamental facts about network arches have been established. The rest of the lecture is mainly on why and how network arches should be built.



Fig. 5. Network arch at Steinkjer, Norway. Span 80m.

## Network arch at Steinkjer.

The author's first network arch was built at Steinkjer in Norway in 1963. Pp. 5b to 6c and P. 57. By mistake there were no rails between the hangers and the traffic. Nobody checked the author's calculations. He does not think that was sensible, but it made the bridge more original. See also (Tveit 64) and (Tveit 66).

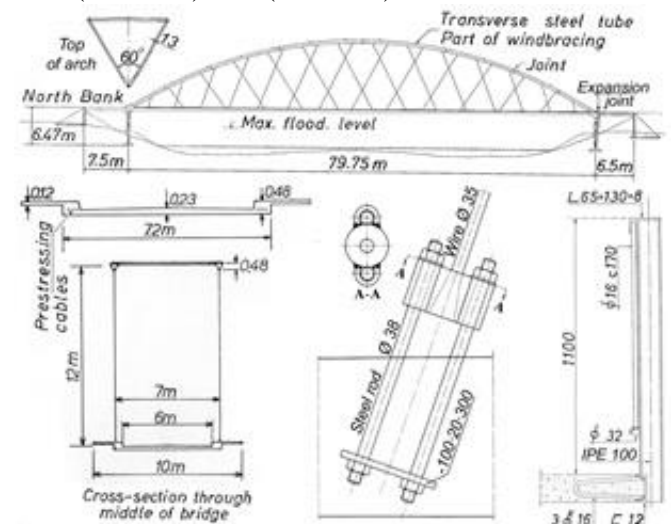


Fig. 6. Structural details at Steinkjer



Fig. 6 gives details of the network arch at Steinkjer. Please note the slim chords. The arches have a constant curvature. The constant change of slope between neighbouring hangers is  $1.8^\circ$ . The slope of the steepest hanger is  $74.4^\circ$ .

The cross-section and the maximum force are almost the same in all hangers. Where the hangers cross, one of the hangers is protected by a split open plastic tube. That prevents wear when they rub against each other. Vibrations in hangers are reduced if they are loosely tied together where they pass each other.

There are prestressing cables in the tie. The hangers are adjustable. They are anchored in the edge beams. The railing is welded to bits of steel channels anchored to the edge of the footpath. The welding here was done slowly with little heat to avoid breaking the bond between steel and concrete.

The author was warned against anchoring steel in the concrete, but it has functioned well for over 50 years. The slight prestress in the tie has contributed to this.

It was also said that the public would not like to have the railing outside the footpath. The 13 cm wide handrail is supposed to make the pedestrians feel comfortable. There have been no complaints.

The handrail is in one piece along the main span. The railing was put up when the concrete was about half a year old. The author expected the main span to become shorter due to shrinkage and creep. That has not happened, but the expansion joint has had a tendency to close. (Tveit 2007).



Fig. 7 shows the bridge before it got its final coat of paint. The architect recommended that we should keep the red colour. The bridge has now got a conventional gray colour. However, seeing the red colour of Chinese arch bridges has convinced the author that the architect was right.

Fig. 7. First coat of paint at Steinkjer

The architect, Terje Moe, was very good. At the time he and the author were both assistants at the technical university in Trondheim. He went on to become a well known professor of architecture.

He said: "Let your design show how the forces run in the structure". He suggested that the distance between the nodes in the hangers should be constant. That is a good idea when the arches are slender and less stiff than the tie.

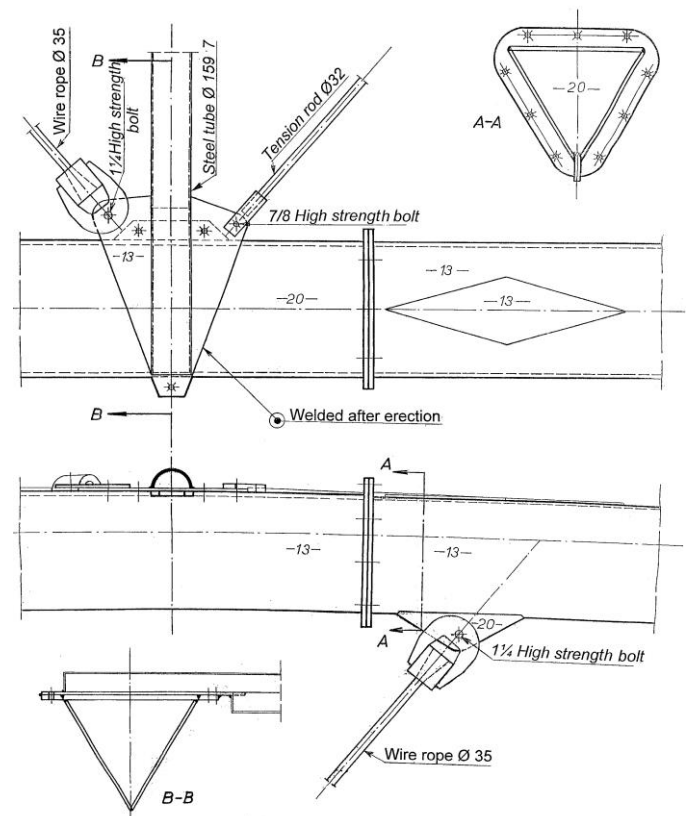


Fig. 8. Shows details of the steel in the arch

Since there is only compression in the cross-section of the arch, the joints are simple flanges. The screws in the flanges are needed only during the erection. P. 56.

Details around the second tube in the windbracing are shown in fig. 8. The first diagonals in the windbracing have the same details as a hanger. The other diagonals in the windbracing are tension rods that have been tightened by screw threads.

The first tube in the windbracing has a smaller maximum force than the second. The two tubes have the same cross-section because a high load might collide with the first tube. Such a collision has actually happened.

The steel structure looks good and was simple to erect, but it was costly to make. Still the network arch was less costly than a competing concrete arch with vertical hangers. If the arches had been universal columns or American wide flange beams, the cost would have been much reduced. The architect was dead against that idea.

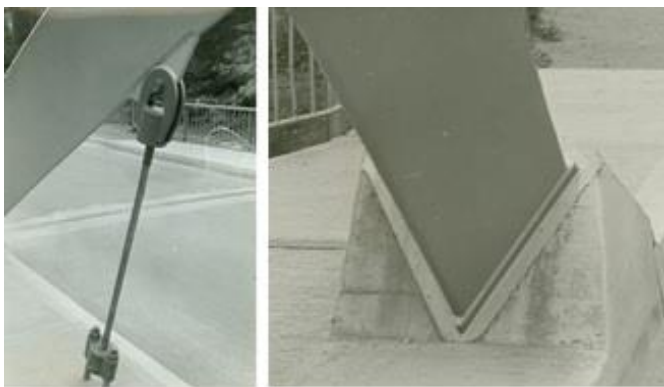


Fig. 9. Hanger and end of arch filled with concrete

Fig. 9 shows a hanger and the end of the network arch in Steinkjer. At the lower end of the hanger the decisive cross-section is under the nuts. Thus the steel rods have ample cross-section just above the concrete. They can take the bending due to colliding lorries. Five hangers have been hit by lorries. The damage is not serious, but it is best not to bend the hangers back. That could possibly increase the damage to the concrete.

The right side of fig. 9 shows the lower end of an arch. The lowest 7 m of the arches are filled with concrete to make them more able to withstand collisions with heavy vehicles.

### Movable bearing.

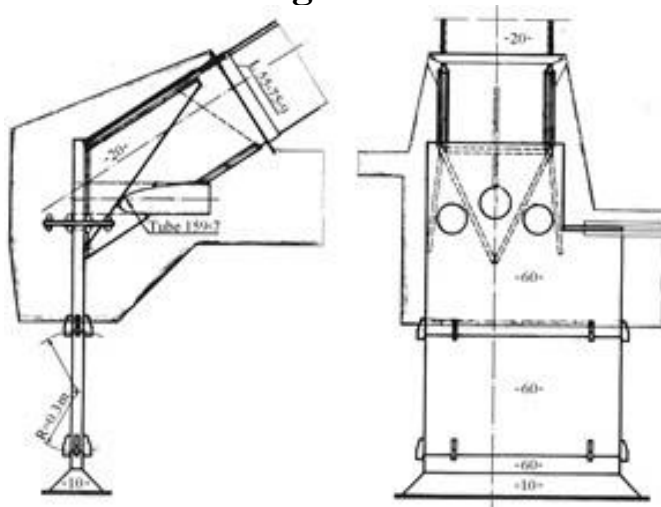


Fig. 10. Shows the moveable bearing at Steinkjer. The prestressing cables are anchored to the plate at the end of the arch. The plate below is as if it was cut out of a cylinder. The plate was thoroughly checked to see if it had a laminar structure.

Fig. 11 shows the influence lines for the network arch at Steinkjer. Can also be found at *p. 57*. Their shape is very much like the influence lines of a truss. In fact the network arch can be seen as a truss with many diagonals that can only take tension. We can see that the axial forces in the arch and lane are very constant. So are the longitudinal bending moments in the tie.

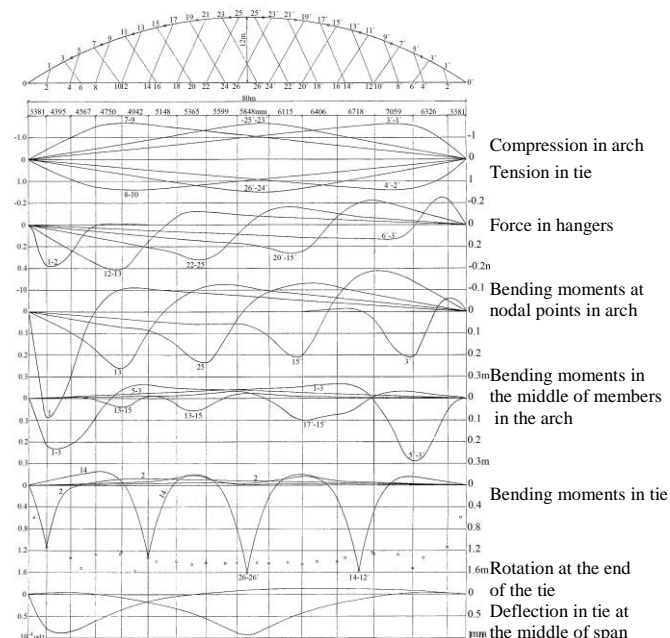


Fig. 11. Shows the influence lines at Steinkjer

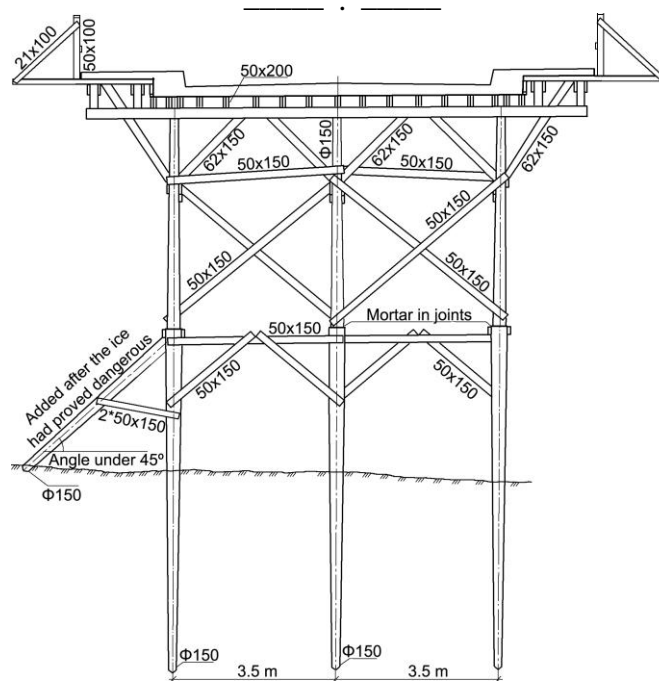


Fig. 12. Scaffolding for the network arch at Steinkjer

After the concrete tie was cast, the arch was supposed to be erected. Then the hangers were supposed to be installed and tensioned till they carried the tie. Then the wooden scaffolding could be removed.

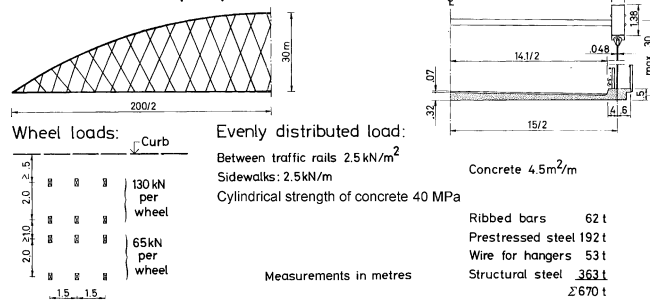
The steel did not come as planned and in the winter the ice swept away 17.5 m of the scaffolding. The tie was sagging about 0.2 m. Cracks of up to 2 mm appeared. They closed again due to the prestressing. Now they can hardly be found.

## Vibrations

Initially there were some worries about the vibrations in the Steinkjer network arch. Measurements showed that the the vibrations were only 20 % of what people thought they were. The asphalt reduced the vibrations and after that nobody worried.

The stiffness and the thin slab give the network arch good resistance to vibrations due to wind. If the hangers are loosely joined where they pass each other, there will be no harmful vibrations due to wind.

#### Network arch, proposal 1980. Danish codes.



#### Bridge at Straubing, built 1977. Codes: DIN

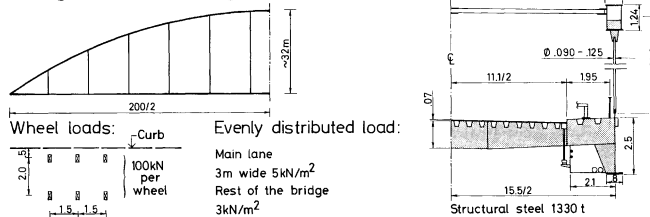


Fig. 13. Data for two bridges

Fig. 13 gives a comparison between a network arch and an arch bridge with vertical hangers. *P. 14* and *15*. The two bridges have nearly the same width and both have spans of 200 m. The two bridges have different chords and rise of the arches. Still they can be compared. The bridge with vertical hangers uses twice as much steel as the network arch. This is impressive since the Straubing Bridge uses no concrete.

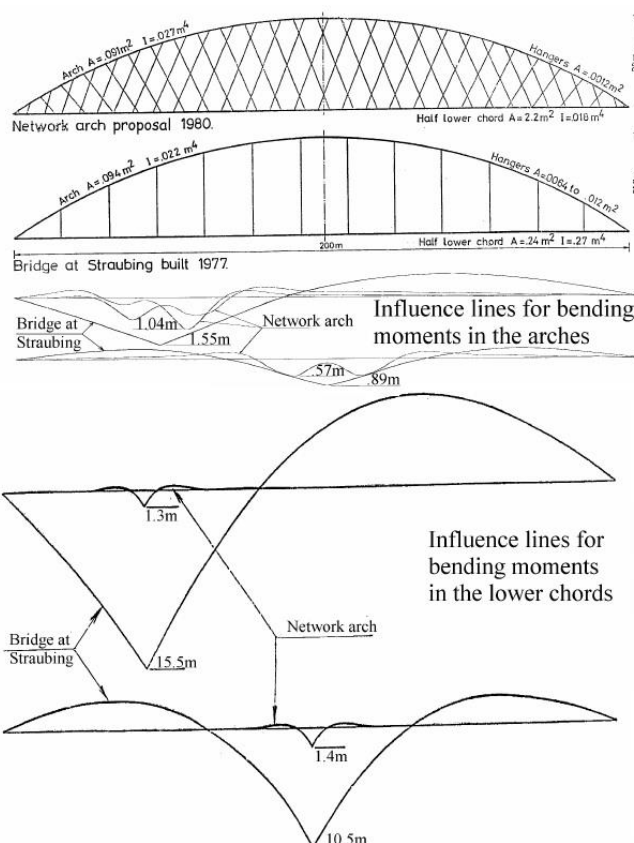


Fig. 14. Influence line for the two bridges in Fig. 13

Fig. 13 shows influence lines for longitudinal bending moments in the chords of the two bridges in fig. 13. The ordinates are much smaller in the network arch, especially in the tie, because the tie in the network arch is very slender.

The biggest influence ordinate for the tie in the network arch is 1.4 m. That is the same as for a simply supported beam spanning 5.6 m. The concrete slab spans 15 m between the arches. Thus the longitudinal bending moment in the tie is normally smaller than the bending moment half way between the arches.

The author believes that because the Straubing Bridge is a steel bridge the arch should have been part of a circle. Then the windportal would have been shorter and the bending moments in the chords would have been more even. Furthermore the axial force would have been more even in the middle 2/3 of the arch.

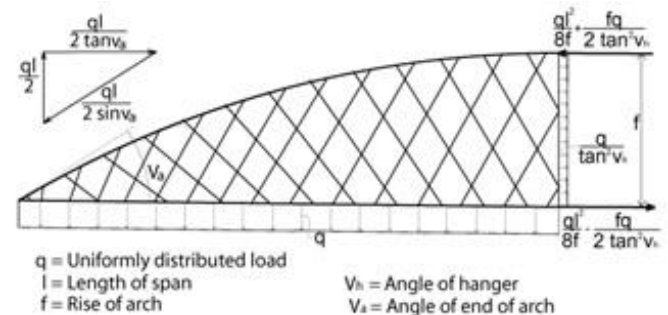


Fig. 15. Formulas for axial forces

Fig. 15 gives formulas for axial forces in a network arch due to an evenly distributed load. Bending moments have rightly been disregarded. The forces at the end of the arch are obvious. In the middle of the span the hanger forces add a little to the axial force in the arch and subtract a little from the tension in the tie.

## Buckling in network arches



Fig. 16. Buckling in network arches (Tveit 66)

Fig. 16 shows the first drawing of buckling in the plane of a network arch. Teich (Teich 2012) finds that buckling out of the plane of the arch is much more likely. See:

[http://www.qucosa.de/fileadmin/data/qucosa/documents/8604/Dissertation\\_Teich.pdf](http://www.qucosa.de/fileadmin/data/qucosa/documents/8604/Dissertation_Teich.pdf) page 226, section 4.2.5.4. When the arch has a constant stiffness, the buckling strength in the plane of the arch is two to three times bigger than the buckling strength out of the plane in the arch.



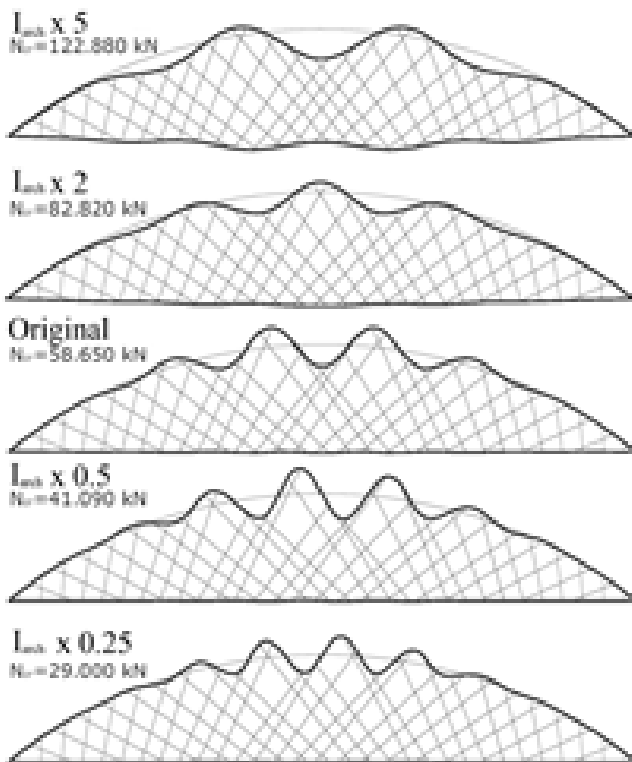


Fig. 17. Buckling when stiffness of arch varies

Fig.17 (Shanack 2008) shows how the buckling load varies with varying stiffness of the arch. Furthermore he found that variation in the stiffness of the tie hardly influences the buckling load in a normal network arch. This simplifies the calculation of the buckling in the arch.

The buckling load depends on the axial load in the arch. Before a geometric nonlinear load-deformation with incremental increases of load is carried out, buckling in the arch can be calculated as the buckling of a bar on elastic foundations.

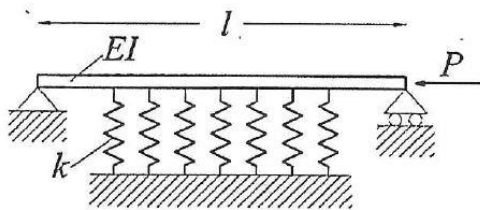


Fig. 18. Beam on an elastic foundation

The formula for calculating the critical load is

$$P_{cr} = \min \left( \left( \frac{n \cdot \pi}{l} \right)^2 \cdot EI + \left( \frac{l}{n \cdot \pi} \right)^2 \cdot k \right)$$

$P_{cr}$  is critical buckling load

$n$  is number of waves in the beam

$l$  is length of bar

$EI$  is stiffness of bar

$k$  is stiffness of support

Teich's and Schanac's formulas assume a constant stiffness of the arch. The extra stiffness at the ends of the arches gives a higher buckling load. Sideways buckling in the arch is normally a decisive loadcase.

## Effect of relaxing hangers

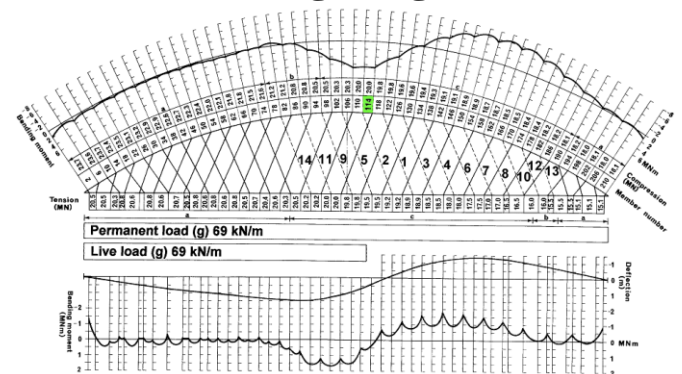


Fig. 19. Forces and deflections due to an extreme skew load on a bridge spanning 200 m

Fig. 19 shows the effect of hangers relaxing. *Pp 67 and 68.* Numbers indicate the sequence of the relaxation of the hangers. The calculations have been done for a live load equal to the dead load. That is, however, not likely to occur.

Moderate skew live load is not dangerous because reduced axial forces compensate for the increased bending moments. See fig. 20. Normally it is of less importance that the relaxation of hangers give reduced buckling stresses in the arch. The relaxation of hangers leads to increased deflection and considerable bending moments in the chords. Where the hangers have not relaxed, the bending moments in the chords are small.

Arch member 114 is the first member in fig. 19 where an increasing skew load gives the same maximum stress as the load on the whole span.

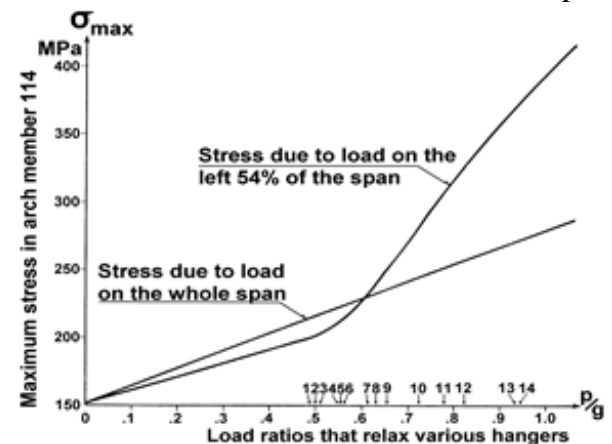


Fig. 20 shows the development of maximum stress in member 114. Along the horizontal axis is the ratio of live load to dead load. You can see what loads make various hangers relax. For moderate live loads, load on the whole span is decisive. After six hangers have relaxed, partial live loads start to give the maximum stress.

For slim network arches it is often best to avoid the relaxation of hangers in the serviceability limit state. This simplifies calculations and it gives less fatigue in hangers.

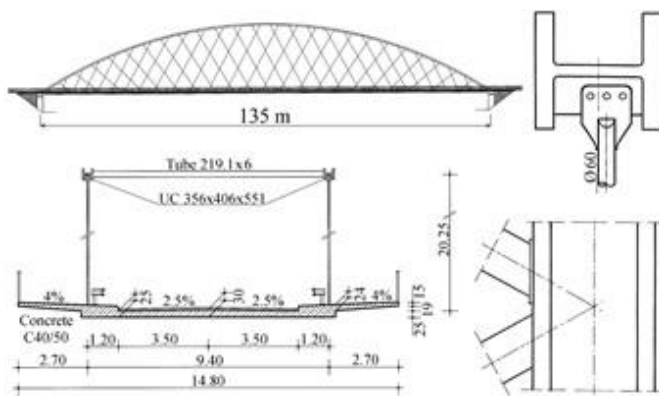


Fig. 21. The Åkvik Sound Bridge

The Åkvik Sound Bridge network arch was the subject of the master's thesis of (Teich and Wendelin in 2001). It was designed according to EU-Norms. Two ways of fastening the windbracing are shown. Calculations can be found on

[http://home.uia.no/pert/index.php/Masters\\_Theses](http://home.uia.no/pert/index.php/Masters_Theses).

A good example of an optimal network arch is shown in fig. 21. It was designed by two students from TU-Dresden in Germany. They did their master's with the author in Norway. The bridge was planned between two Norwegian islands with a total population of 3500 inhabitants. The foreseeable volume of traffic is so little that fatigue was no problem. EU loads and codes were used. A way of fastening the hangers is indicated. The master's theses can be found here: [http://home.uia.no/pert/index.php/Masters\\_Theses](http://home.uia.no/pert/index.php/Masters_Theses).

One of the students, Mr Teich, defended his doctoral thesis on network arches in 2012. See [http://www.qucosa.de/fileadmin/data/qucosa/documents/8604/Dissertation\\_Teich.pdf](http://www.qucosa.de/fileadmin/data/qucosa/documents/8604/Dissertation_Teich.pdf). It is interesting to compare the bridge in fig. 21 to bridges with vertical hangers built in Germany.

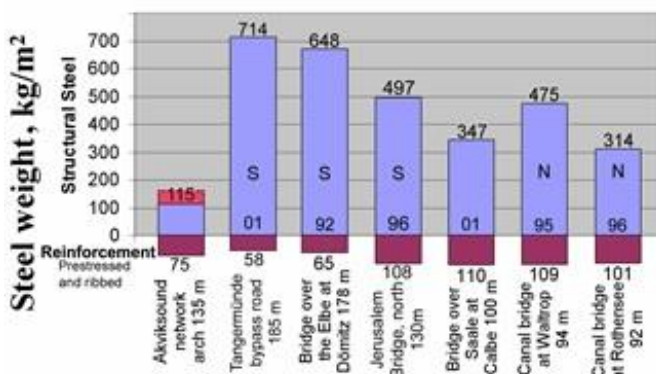


Fig. 22. Comparison between a network arch and arch bridges with vertical hangers

In fig. 22 the students' network arch is compared to German arch bridges with vertical hangers. The arch bridges with vertical hangers use much more steel than the network arch.

The spans and the year when the bridges were built are given. N means that there is no windbracing. S means that the arches slope towards each other.

The German bridges have steel beams in the tie. Still the network arch uses about the same amount of reinforcement without steel beams in the tie. Part of the reason for this is the high amount of minimum reinforcement that is needed in the concrete on top of the elongating steel beams. The reinforcement in the German bridges is much more complicated than the reinforcement in the network arch.

The bright red quantity of steel in the Åkvik Sound Bridge stems from the extra steel weight if a temporary lower chord is used for the erection. The steel weight in the temporary lower chord costs less than the rest of the steel because the lower chord needs no corrosion protection.

According to an extensive survey by (Herzog 75) most other steel bridges use about the same amount of steel as arch bridges with vertical hangers. Later we will compare the cost of the Calbe Bridge to the cost of a network arch of the Åkvik Sound type.

The reader is right in thinking that steel weight is not the only thing that matters. Fig. 23 looks at other factors.

Aesthetics	Bulkier bridges
Adaptability	2 to 8 times deeper lower chords
Fabrication	15 to 30 times longer welds
	More complicated details
Corrosion protection	3 to 7 times more surface to protect
Maintenance	Other concrete parts need much more maintenance than concrete slabs with a slight prestress.
Erection	Erection is more expensive
•On sidespans	with 2 to 4 times more steel
•Floating into place	
•Erection on ice	

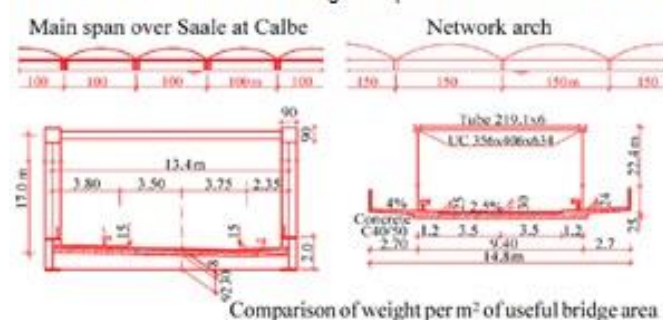
Fig. 23. Differences between optimal network arches and arch bridges with vertical hangers

Bridges with vertical hangers are bulkier. Therefore they do not look so good. They have two to eight times deeper chords. Thus they lead to longer ramps and it is not so easy to attach roads at the ends of the bridge.

Other concrete parts need much more maintenance than concrete slab ties with a slight prestress. Erection is more expensive with 2 to 5 times more steel to erect. We will come back to erection later.

## Comparison of materials and cost

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



Structural steel incl. prestressing steel	Saving	58%
Reinforcement	"	34%
Concrete	"	24%
Weight to be moved during erection	"	46%
Pillars are the same for both bridges	"	33%
Savings in cost are probably 35 - 45% per m² of useful bridge area.		

Fig. 24. Comparison of materials and cost in network arches and other arch bridges

In fig. 24 the German arch bridge in Calbe is compared to a network arch of the Åkvik Sound type spanning 150 m. *Pp. 93a to 93b*. The network arch has longer spans because its steel weight is smaller and increases more slowly with an increased span. Quantities per m² of useful bridge area are compared. (Tveit 2013a P. F-1 to F-2)

Less weight has to be moved during erection.

The pillars are the same for both bridges. The saving in cost is probably between 35 and 45 % per square metre of useful bridge area. There is more on this on *P. 93a* of "The Network Arch" at [http://home.uia.no/pert/index.php/The\\_Network\\_Arch](http://home.uia.no/pert/index.php/The_Network_Arch).

To counteract big deflections in simple slabs between arches, prestressed reinforced polymer fibers could be attached under the slabs. The attachments could be fastened by glue after the bridges were finished, or could be put in place when the bridges were built, hoping that they would not be needed.

## Network arches made of concrete

Since the arch in network arches has mainly axial forces, should we not make the arch of concrete? We should, if the cost of formwork is not too big. In long bridges with many spans all the concrete spans could be made on the shore and then be floated to the pillars.

The author has made a comparison between the western part of the Great Belt Bridge built in Denmark and an alternative using a network arch. See p. 50.



Fig. 25. Comparison between beam and network arch alternatives for the West Bridge in the Great Belt link

Now the author will go back to the beginning. After his graduation the author got a grant to study for one year at the technical university in Aachen in Germany. *P. 16*. Network arches took up most of his time. Nobody else seemed interested in arch bridges with inclined hangers.

Professor Phillip Stein was very good to him. He helped the author to get an opportunity to build his first model of a network arch. He seemed relieved and slightly surprised at how well the model tests supported the author's ideas on the relaxation of hangers.

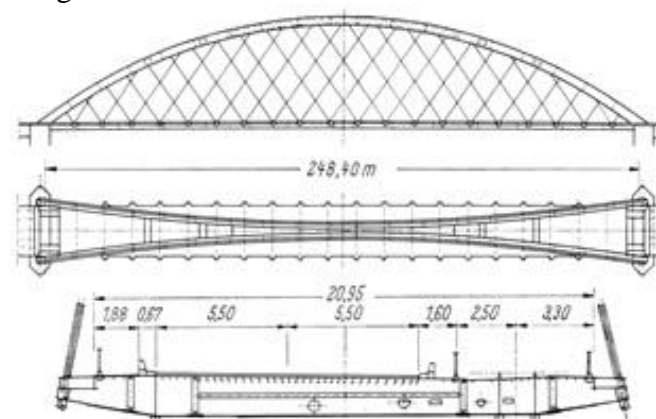


Fig. 26. The Fehmarn Sound Bridge, Germany. 1963

This bridge was finished in the same year as the author's two Norwegian network arches. *P. 17*. At first the author thought that it was a coincidence that this bridge was a network arch. Later he found that Professor Stein had written the 100 year history of the firm Gutehoffnungshütte that built this bridge. (Stein 1951).

The history of Gutehoffnungshütte was published a couple of years before the author had come to Aachen. In a letter Professor Stein confirmed that he may have transferred the idea of the inclined hangers to Gutehoffnungshütte.





Fig. 27. Bridge from the author's Ph.D. thesis, 1959

In fig. 27 the arches slope towards each other. This reduces the windbracing and the bending in the wind-portal, but it increases the span of the slab or the transverse beams in the tie. The sloping arches lead to increased steel weight. (Tveit 1959).

At that time the author suggested hangers meeting in the same point and a constant slope of the hangers. Today he would not do that.

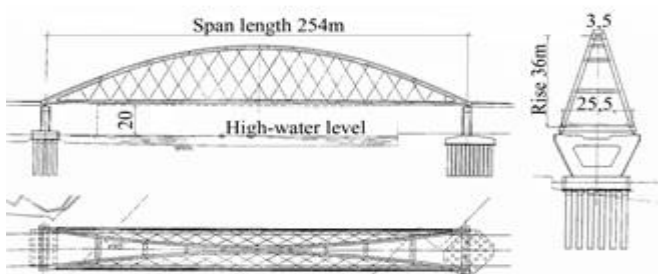


Fig. 28. The Shinhamadera Bridge.

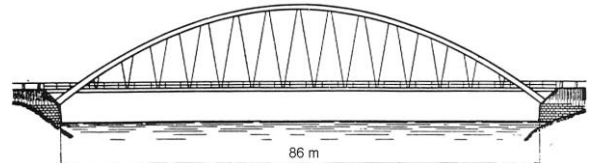
Professor Masao Narouka saw model tests of the Fehmarn Sound Bridge in TH-Hannover in 1960. He took the idea to Japan where it has been flourishing. From there it has spread to other countries. *P. 18.* (Narouka 1977) (Yoshikava 1993).

The Japanese call these bridges “Nielsen-Lohse bridges”. The name seems a bit misplaced to the author. The Shinhamadera Bridge is the longest Japanese network arch. It spans 254 m.



Fig. 29. Lifting of the Shinhamadera Bridge. The tide helped in putting the main span in place.

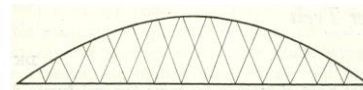
## Nielsen bridges



An early Nielsen bridge. Built in Sweden before 1930.



The longest Nielsen bridge. Castelmoron 1933. Span 145 m.



Nielsen never crossed the hangers of his bridges, but in a patent document in 1926 he showed crossing hangers.

Fig. 30. Various Nielsen bridges

Around 60 Nielsen bridges were built in Sweden between the two world wars. Part of the author's master's thesis was on the calculation of these bridges where hangers could relax. That was a difficult task before computer programs were available. In his doctoral thesis in (1929) O. F. Nielsen explained how to do it. *Pp. 54 – 55.* Constant slope of hangers simplified the calculations.

Nielsen used transverse beams in his bridges. That is why there are two hangers in each nodal point in the tie. The longest Nielsen Bridge was built in Castelmoron in France. *P. 12.* The hangers in the Nielsen bridges relax due to ordinary loads. Still only one or two of the hanger rods in the Nielsen bridges in Sweden have broken in their around 80 years of existence.

Crossing hangers would have made the calculations of Nielsen bridges much more difficult. Nielsen never crossed the hangers in his bridges, but in a patent document from 1926 he showed crossing hangers.

In the author's master's thesis he suggested that the hangers should cross each other many times. That was a good idea because the loads had increased and the stronger materials had led to more slender chords.

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## Temporary tie

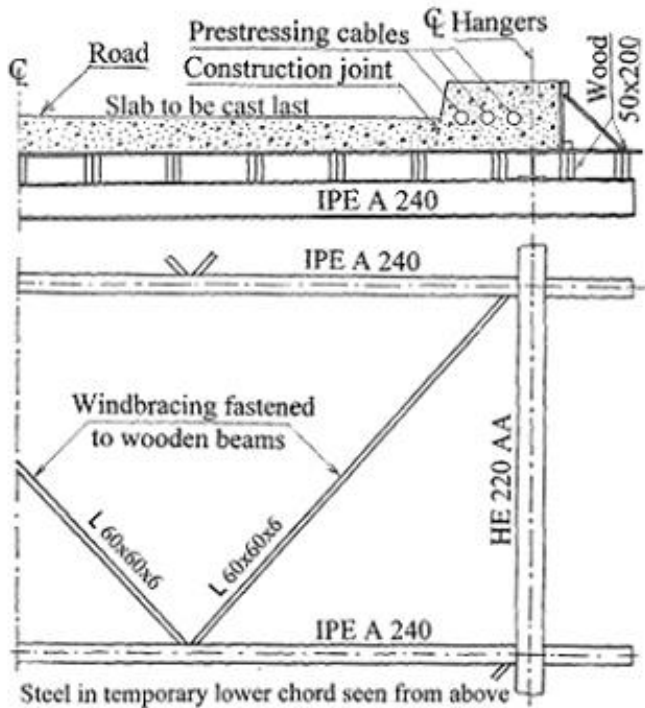


Fig. 31. Temporary tie for a network arch

Fig. 31 shows a temporary tie for the erection of a network arch. 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. *Pp. 29k to 30a and Pp. 50a to P. 50b.*

First the end beams and the concrete around the curved parts of the prestressing cables are cast. After that a small force in the prestressing cables can reduce the stress in the longitudinal beams in the tie. Then the edge beams are cast from both ends to avoid relaxation of hangers. Then the concrete slab is cast.

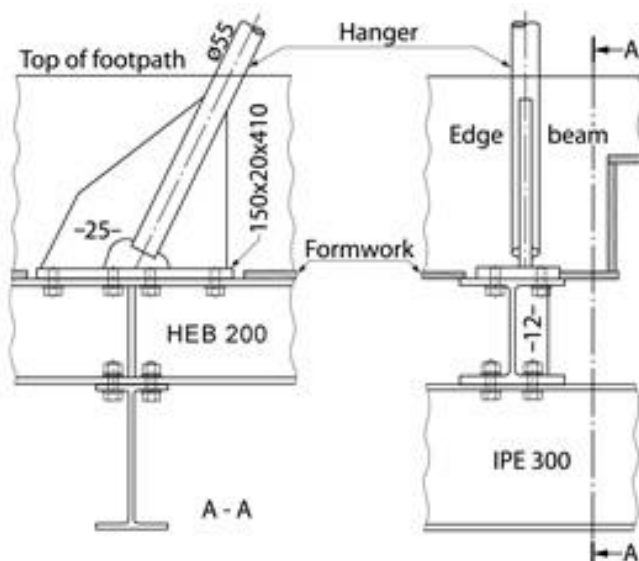


Fig. 32. Shows joint in temporary lower chord

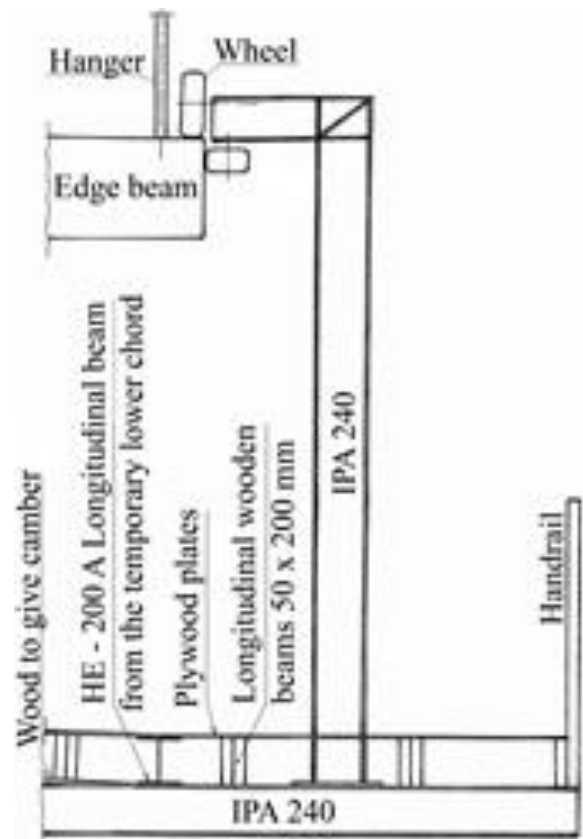


Fig. 33. Wagon for removing temporary lower chord

Fig. 33 shows a wagon for removing the formwork and the temporary lower chord of a network arch. *Pp. 52 to 54.* The floor in the removal wagon has been a part of the formwork for the casting of the tie. It has been lowered after the casting was finished. You can see the longitudinal beam from the temporary lower chord.

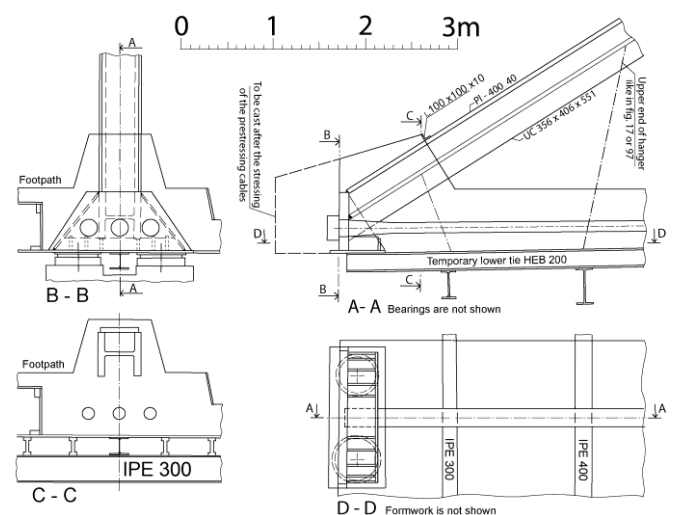


Fig. 34. End of span with a temporary lower chord

Fig. 34 shows the end of a finished network arch where a temporary lower chord is about to be removed. *P. 30.* The temporary lower chord ends in a cavity between the bearings. This cavity has room for hydraulic presses if bearings are to be changed.





Fig. 35 shows lifting of a steel skeleton

Fig. 35 shows the lifting of the steel skeleton of the Åkvik Sound network arch (See page 7) by the biggest Norwegian floating crane. The floating crane has a capacity of 600 t. The load is 410 t. The steel skeleton weighs 230 t. The remaining 180 t is formwork and reinforcement. How much formwork and reinforcement that should be lifted must be decided in each case.

Normally one crane at each end of the span will do the lifting. Floating cranes that can lift over 3000 t are available. It seems that finished spans over 300 m can be produced on shore to be lifted onto the site. If the whole network arch is made of concrete, the spans could be up to 250 m.

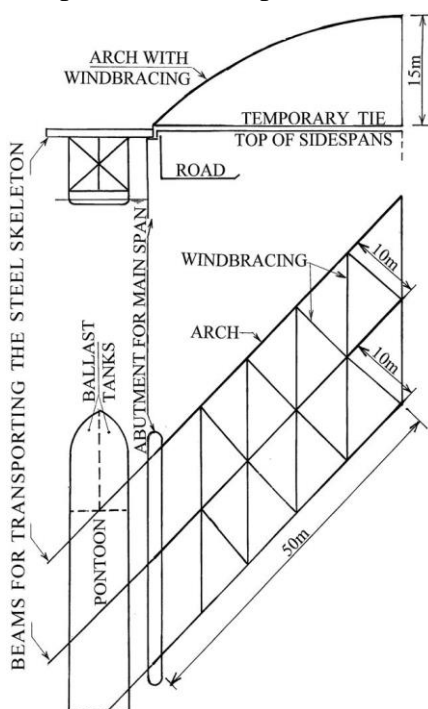


Fig. 36. Lifting by pontoons

If the shape of the steel skeleton is right, then no adjustment of hangers is needed later.

While the beams on top of the pontoon are tied to the abutment, the steel skeleton is rolled to the middle of the pontoon. Then the pontoon is pulled across the canal. Finally the skeleton is rolled onto the abutments and the concrete tie is cast.

Fig. 36 shows the first stage of the erection and transport of a skew bridge across a canal. The span is 100 m. *P. 20*. Three arches reduce the necessary thickness of the concrete tie. The structural steel, supplemented by a temporary lower chord, is erected on the side spans.

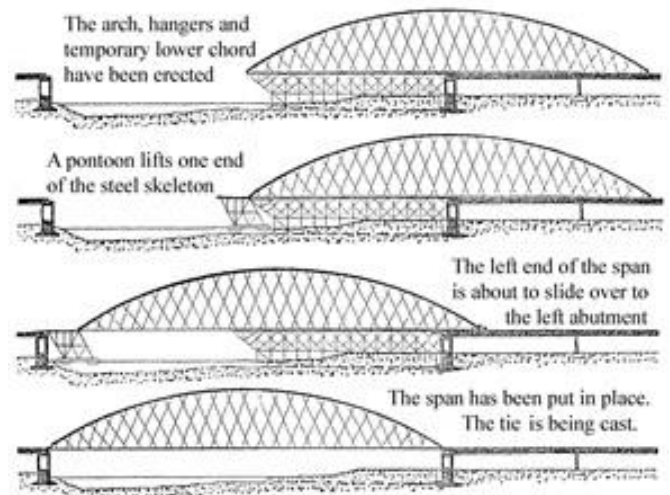


Fig. 37. Erection of network arch spanning 200 m

Fig. 37 shows how a network arch can be erected at the site at Straubing. *P. 15*.

## Erection on ice

In cold climates steel skeletons of network arches can be erected on ice, and be lifted on to the pillars. *P. 30b*. Around 0.7 m thick ice will usually prevent water from seeping onto the ice during the erection.

In the spring the concrete tie can be cast. See (Tveit 2013) *p. 30b*. Sufficient ice thickness can be achieved by pumping water onto the ice or by spraying drops of water into cold air.

## Railway bridges

Network arches have around 10% of the deflections that we find in arches with vertical hangers. (See fig. 57). This is a great advantage, especially in bridges for high speed railways.



Fig. 38. Double track network arch railway bridge

Fig. 38 shows a double track railway bridge spanning 100m designed by two German students from Dresden. They did their master's thesis with the author in Norway. (Brunn and Schanack 2003) *Pp. 32 to 33*. Schanack finished his Dr.-Ing. in Spain in the spring of 2008. (Schanack 2008). He is now a professor in Chile.

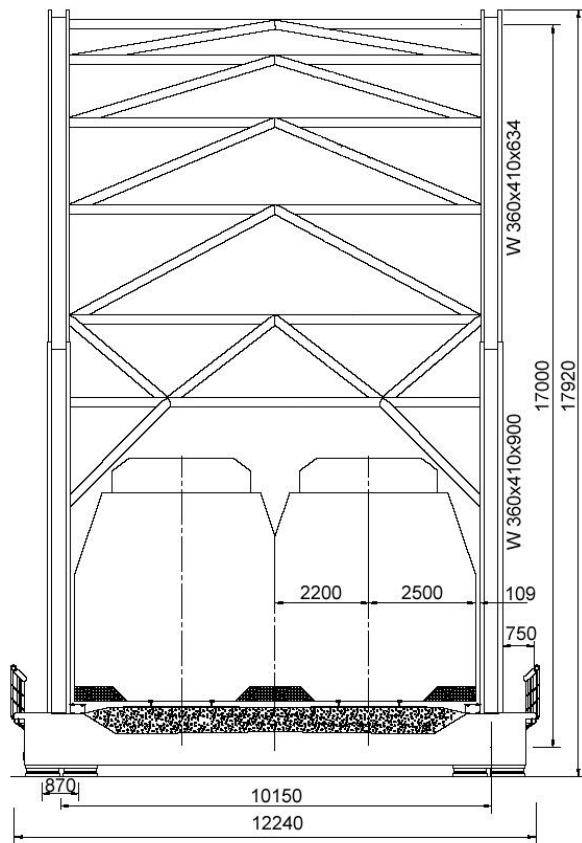


Fig. 39. Shows the network arch in fig. 38

Here the network arch in fig. 38 is seen from one end. It has universal columns in the arches and prestressed concrete in the tie.

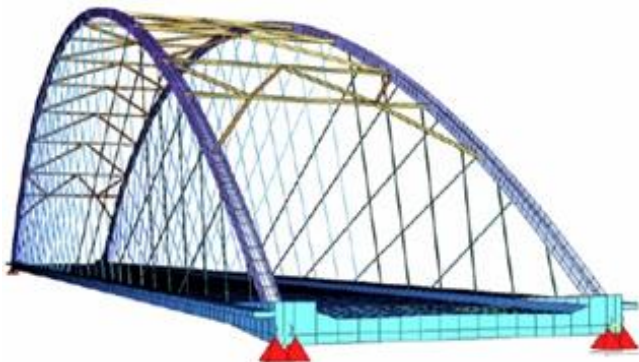


Fig. 40. The 3-D FEM model used for calculations

The extensive and valuable calculations can be found on the internet. They are written in English. [http://home.uia.no/pert/index.php/Masters\\_Theses](http://home.uia.no/pert/index.php/Masters_Theses).

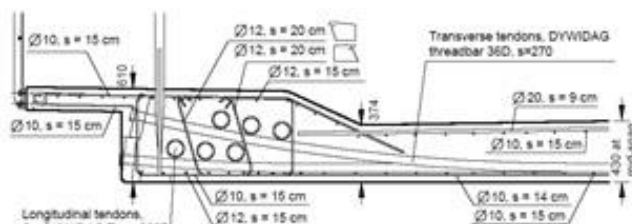


Fig. 41. Tie of a railway bridge spanning 100 m

Fig. 41 shows reinforcement in the tie of the bridge. Half the anchors of the prestressing rods are passive. The lower ends of the hangers are tied to prestressing anchors.

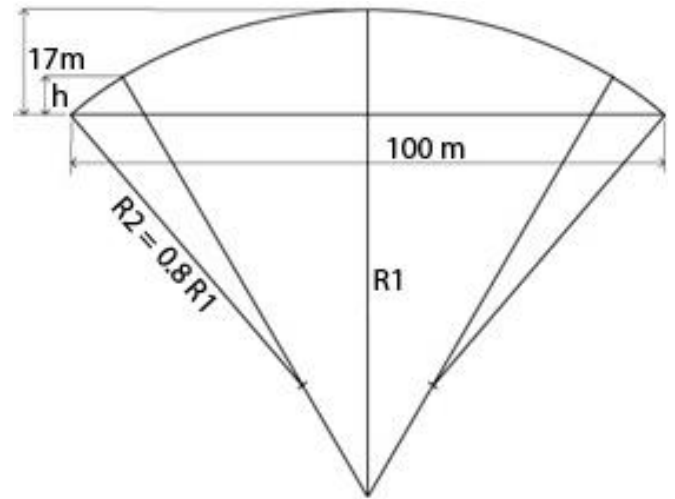


Fig. 42. Curvature of a network arch

Fig. 42 shows the curvature of the bridge in fig. 38. The reduced curvature near the ends of the arches will give shorter wind portals and a more constant force in the rest of the arch. In most of the arch they used a constant angle between arch and hangers.

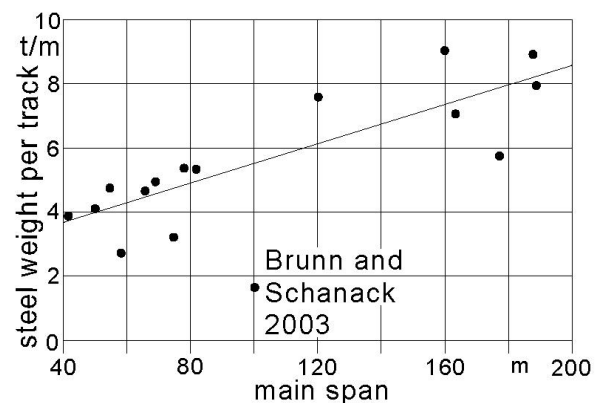


Fig. 43. Steel weight in railway bridges

In fig. 43 the steel weight per meter of track of railway bridges is compared. It can be seen that Brunn and Schanack's bridge uses about a third of the steel needed for other railway bridges.

## Bridge for rails and roads

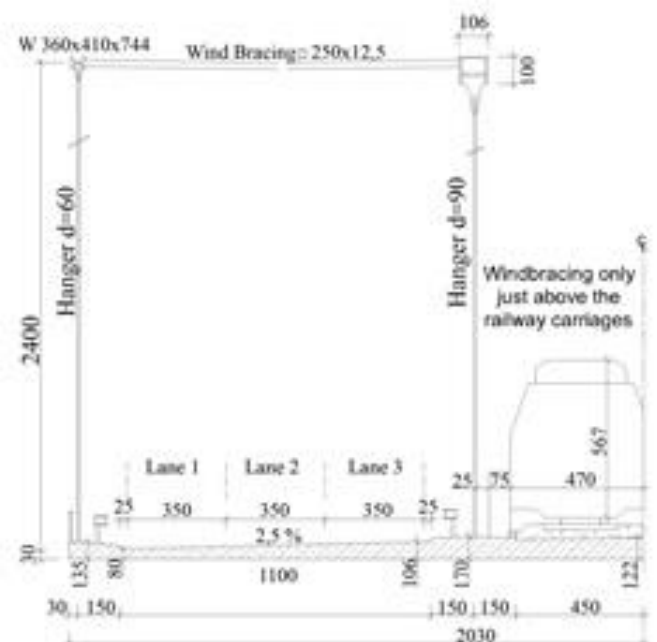


Fig. 44. Shows half of a bridge designed by M. Räch



Mathias Räck (2003) was another student from TU-Dresden. He did his master's thesis with the author in Norway. His master's thesis can be found on [http://home.uia.no/pert/index.php/Masters\\_Theses](http://home.uia.no/pert/index.php/Masters_Theses). The bridge has three lanes in each direction and two railway tracks in the middle. P. 34.

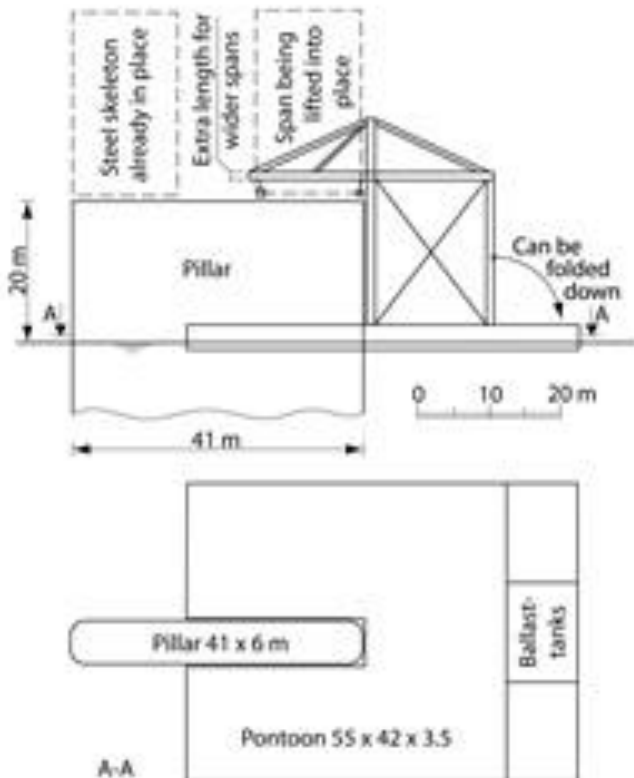


Fig. 45. Crane to move steel skeletons to the pillars

The crane in fig. 45 can be used to move the 160 m long steel skeleton of Räck's bridge to the pillars. P. 54. The crane can be folded down to pass under existing bridges. The boom has extra length so that the crane can be used for wider network arches.

When the pillars are higher than 20 m, it might be better to use pontoons and cranes for the transport. Depending on availability, cranes on the pillars or floating cranes could be used.

The author refers to the works of his students, because they have tried out his ideas, and their calculations can be put on the internet. Firms that design network arches have ideas of their own, and have to meet the wishes of bridge authorities. Their calculations are not readily available.

For many years the author published his results hoping that the network arch would become popular. He has been wondering why it took so long. An obvious explanation might be that optimal network arches are not economical. He is not willing to accept this explanation and will try to come up with other reasons.

The network arch is not overly complicated, but all design offices have a shortage of engineers that can be trusted with the design of their first network arch. These engineers have many other tasks that have high priority.

For a firm it might not be economical to find out all about network arches in order to design just one bridge. When a big project comes along, most public bridge offices would like to use well tested ideas tempered by some ideas of their own. Besides, they are always short of time.

Network arches require co-operation between steel firms and concrete firms. The firms might have less motivation for co-operation because network arches use little steel and little concrete.

Bridge authorities have better reasons for building network arches, but the introduction of the network arch would create extra work for them. If they decide to design their first network arch, they would have fewer man hours to spend on other bridges. If the bridge authorities do not promote the network arches, it is hard for others to do it. It is probably mainly conservatism that has held the network arches back.

## Schulenburg Bridge

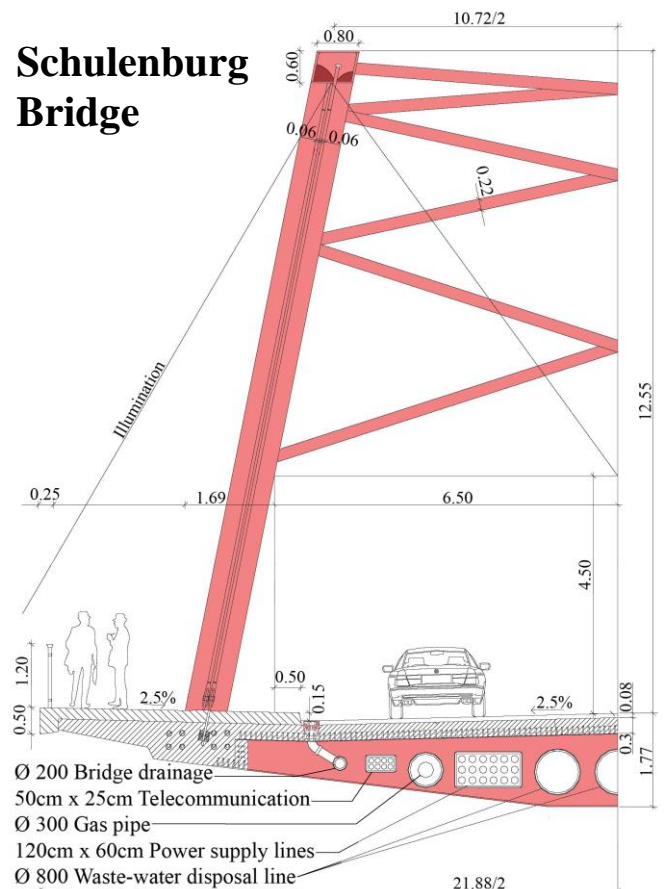


Fig. 46 was suggested for a site in Berlin

The bridge in fig. 46 has a span of 90 m. It was the subject of the graduation thesis of Wolfram Beyer in 2005. Frank Schanack was adviser. The slide shows another way of putting the tubes under the tie. This leads to extra height of the tie.

It has transverse steel beams, but the longitudinal beams in the tie are made of concrete. In this way the prestressing cables do not give compression in the steel beams in the tie. Steel and concrete are used most efficiently in all members of this bridge.

This design won a prize for outstanding master's thesis at The Technical University in Dresden in Germany.



Fig. 47. Schulenburg bridge in its surroundings

Fig. 47 shows that the bridge does not look clumsy in spite of the deep beams, but it would have looked better if the tie had been only half a metre deep.

## Network arches that have been built



Fig. 48. Bridge built in Czech Republic in 2004

Fig. 48 shows a network arch that was built in Bechyne in the Czech Republic in 2004. *Pp. 92 to 92c.* It has a span of 41m, and replaced an old bridge. The slim tie makes ample room for the 100 years' flood. The existing roads on both sides of the bridge needed only small alterations.

The Czech engineer Ladislav Šašek (2005), (2006) heard about the network arches, consulted the author's home page and designed the Bechyne Bridge. The author heard about the after it was finished. Fig. 49a shows how tubes are hidden under the footpath.

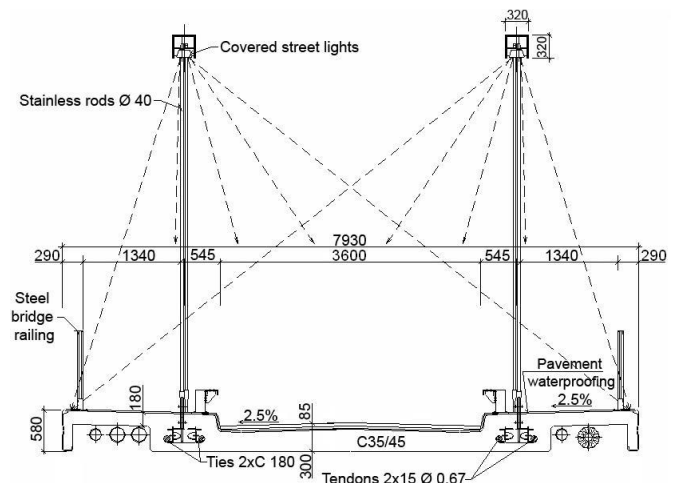


Fig. 49. Cross-section of Sasek's bridge in Bechyne

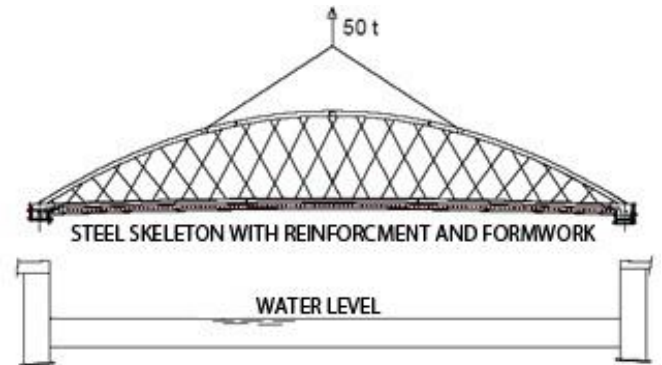


Fig. 50. An advanced method of erection

Sasek suggested this method of erection for the steel skeleton of the network arch in Bechyne. The steel skeleton weighs about 30 tons. 20 tons of the load is formwork and reinforcement.

## Network arch in Rhode Island USA

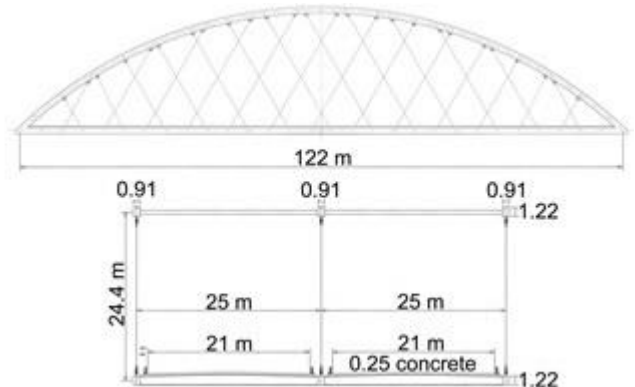


Fig. 51. Network arch with three arches in USA

Fig. 51 shows a network arch in Providence. It was finished in 2007. *P. 19.* The span is 122 m.



Fig. 52. Steel skeleton for the bridge in Rhode Island

Fig. 52 shows the Providence network arch before it is floated 24 km to the site.



## Bridge for a motorway in Germany

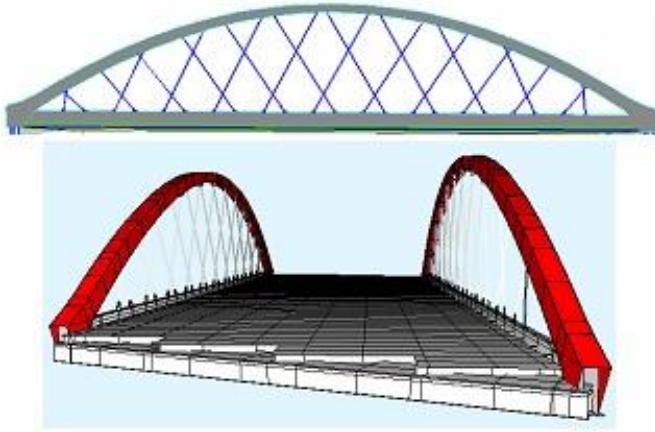


Fig. 53. This bridge was built in 2005

The bridge in fig. 53 has two parallel spans that are 27.4m wide. The span is 88m. It was built over a motorway in Saxony, Germany. It is so wide that there had to be steel beams in the tie. Compared to an alternative with vertical hangers it saved 30% of the steel.



In fig. 54 the four arches look like three. It is an optical illusion that the tie seems to be sagging. It should have had a slight upwards curvature.

## Blennerhassett Bridge



Fig. 55. The world's longest network arch. Span 268m

The Blennerhassett Bridge over the Ohio river was opened in June 2008. The distance between the arches is 32.6m. (Wollmann, Zoli 2008)

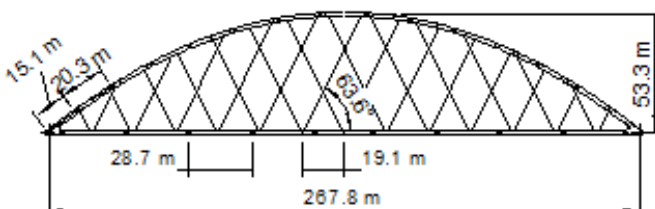


Fig. 56. Network tied arch elevation

Initially the design envisioned a conventional tied arch with vertical hangers. However, such a system is sensitive to a symmetrical traffic loading, particularly in the case with one-half of the span length loaded. Given the great width of the deck and the correspondingly large live load, it was not possible to meet the design criteria for deflection limits.

With the network hanger arrangement the structural system takes on truss-like characteristics, e.g. greater stiffness under non-uniform loads and smaller chord bending moments. For the case of the Blennerhassett Bridge comparative studies showed that with the network hanger arrangement live load deflections were reduced by a factor of nearly 11, compared to a system with exactly the same member size but using vertical hangers (Fig. 57). Bending moments in arch rib and tie girder were reduced by a factor of 4 and 5, respectively.

Another advantage of the network tied arch system is its resilience under accidental extreme load cases, such as the sudden loss of a cable or loss of the moment capacity of the tie girder due to partial fracture. See Zoli and Steinhouse (2007).

With the inclined hanger arrangement cable spacing along the rib is smaller. Therefore loss of a cable has a less detrimental impact on bending moments in the arch, including second order effects, than with vertical hangers.

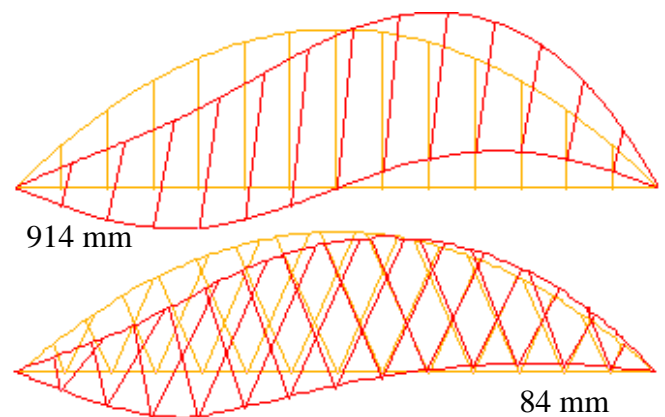


Fig. 57. Live Load deflections



Fig. 58. Arch erection

The method of erection was influenced by the need to keep the Ohio river open at all times. See also (Tveit 2013a. Pp. H-23 to H-25).

## The worlds longest network arch

A network arch spanning 380 m over the river Ob was opened in Novosibirsk in the autumn of 2014. President Vladimir Putin came to the opening. Design of the bridge started after the authors lecture in Moscow 2008.



Fig. 59 Bridge over Ob in Novosibirsk

The bridge has 6 lanes of traffic. It is 38 m wide. Height of the tie is 2,5 m. Height of the arch is 3 m. Visually the ~72 m high arch resembles a gigantic red bow that is one of the sibiran symbols represented in the coat of arms of Novosibirsk. More information can be found at:

[http://www.stpr.ru/eng/projects/1045/?sphrase\\_id=252](http://www.stpr.ru/eng/projects/1045/?sphrase_id=252)

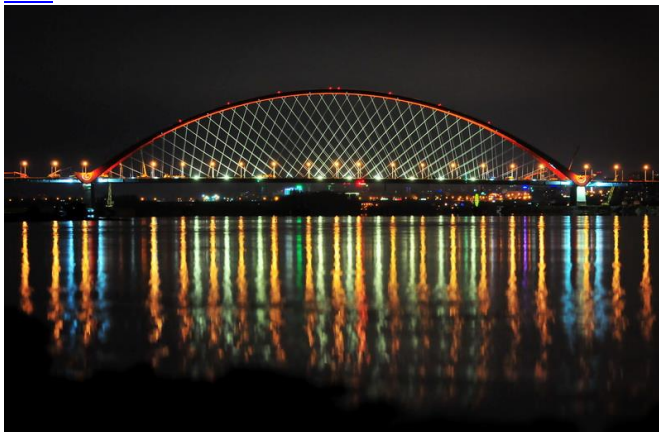


Fig. 59a Bridge over Ob in Novosibirsk at night

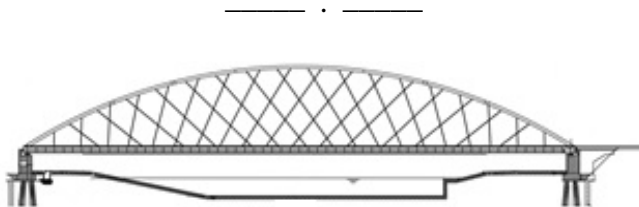


Fig. 60. The Flora Bridge spans 132.6 m. Pp.35-36

Network arches with concrete ties are lighter and stiffer than other steel bridges using the same amount of steel. Resistance to earthquakes will be good. This is due to the high strength to weight ratio and much reinforcement in the edge beams. It is important that bridges remain intact after an earthquake. Then help can be brought in fast.

## The Svinesund Bridge



Fig. 61. The Svinesund bridge, Norway/Sweden

The bridge in fig. 61 was built to commemorate the peaceful dissolution of the union between Norway and Sweden in 1905. The span is 247 m. The two steel boxes are the same for the 4 km length of the bridge. The main span has vertical hangers.

A group of the author's students designed an alternative network arch. The students needed about 4000 tons less steel. Otherwise the quantities were not very different. The students' quantities of reinforcement and concrete are given in parentheses. Reinforcement used was 970 t. (1200t). Concrete 5300 m<sup>3</sup> (5500 m<sup>3</sup>).

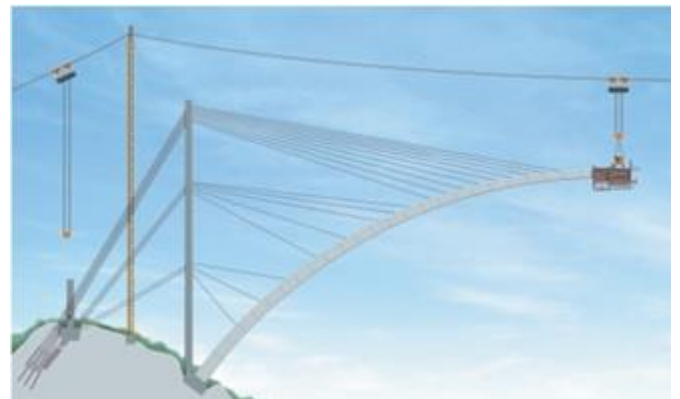


Fig. 62. Shows the casting of the arch

Fig. 62 shows the extensive arrangement for casting the arch of the Svinesund Bridge. It is a fairly standard method for erecting arch bridges.

In fig. 63 you see the lifting of the middle of the tie of the main span. The weight to be lifted was 1450 tons. It was not simple.

The steel sections were produced in Germany. They were transported on a pontoon to a harbour built in Svinesund. There they were assembled to be transported to the site.





Fig. 63. Lifting of the steel tie of the arch bridge

The students' bridge is shown in fig. 64. It spans 135 m. The two spans could have been completely finished on a quay 20 km from the site. Two big floating cranes that could lift at least 800 t each could transport the students' main spans to the site. The students' quantities are preliminary.



Fig. 64. The students' alternative bridge

The author's wife prefers the present bridge. Furthermore it seems right to commemorate the peaceful dissolution of the union between two countries by building a beautiful bridge between them.

In real life the students' bridge would have looked better than in the picture. The hangers would hardly have been seen. The combined height of the four arches would have been about half of the height of the arch in the bridge that was built. The tie in the bridge that was built is about 7 times as deep as the tie in the students' spans.

I mention the Svinesund Bridge to illustrate another point. Like in the Svinesund Bridge, big roads often have two lanes plus a stopping lane in each direction. The two directions can be built meters apart. If the road goes through tunnels, that is a must. If network arches were used, two parallel spans would be lighter than one and easier to erect.

If universal columns were used, the very slender arches would look good. Sometimes the same temporary lower chord could be used for both spans.

In many places heavier traffic can be expected in the future. Then it might be economical to build one span sufficient for carrying the present traffic. Two parallel spans should be planned, and the second span should be added when the first span is congested.

It seems to the author that the network arch with a concrete tie might be the optimal solution for bridge spans between 40 m and up to and over 300 m. Maybe it competes best for spans between 80 and 150 m, but the site is more important than the span.

## Future developments

Since more than 100 network arches have been built in around 20 countries, the future of network arches looks bright. The author believes that the most important future developments of network arches will be on methods of erection.

Tubular arches pumped full of concrete after the steel skeleton have been moved to the pillars have two advantages:

1. Smaller cranes or pontoons will be needed for the erection.
2. Tubular arches has a third of the wind force compared to rectangular sections.

The steel skeleton to be moved can be even bigger, if the tie is a concrete slab that is cast after the steel skeleton is moved to the pillars. These developments will be more important in network arches spanning more than 250 m.

The author regrets that old age prevents him from following up these ideas by thorough calculations, but he will support anybody who wants to do so.

Remembering that «Predictions are difficult, especially about the future.» the author will stop here.

## Summing up

**Network arches are equally well suited for road and even better suited for rail bridges.**

**They use very little steel.**

**An optimal network arch is likely to remain the world's most slender arch bridge. The slim chords are pleasing to the eye and do not hide the landscape or cityscape behind them.**

**If the bridge is not too wide, the tie should be a concrete slab. Concrete ties with small edge beams can be used for up to 15 m between the arches.**

**Efficient methods of erection are available.**

**Since the network arch needs little materials, a high percentage of the cost will be employment.**

**The poverty in some parts of the world is one more reason for using the network arch at suitable sites.**

**Depending on the site, the network arch can save up to 40% of the cost and 70% of the steel.**

**If the network arch had been a well known type of bridge, it would have been hard to argue convincingly for arch bridges with vertical hangers and many other bridge types.**

**Conservatism is the main obstacle to the building of network arches.**



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