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# Concrete in the optimal network arch

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ABSTRACT: The network arch is an arch bridge with inclined hangers that cross each other at least twice. If hangers cross each other only once, it is a Nielsen bridge. When the ties are a thin concrete slab, the network arch uses less than 2/3 of the steel needed for arch bridges with vertical hangers. A network arch is likely to remain the world's most slender arch bridge. The arches can be made from universal columns of American wide flange beams that come from the steel works with the desired curvature. In many equal spans in long bridges the arches can be made from high strength concrete. Network arches have a pleasing appearance and do not block the view to the landscape and cityscape behind them. A temporary tie can be used in the erection. Spans of up to 300 m can be finished on shore and be lifted onto the pillars by big floating cranes.

## 1 INTRODUCTION

The Bolstadstraumen Bridge in fig. 1 has a span of 84 m. It was finished in 1963. p. 7 and 8. This is short for page 7 and 8 in (Tveit 2007), which can be found on the internet. It is much simpler to find something on the internet than getting out a usual reference from a library. In fig. 1 you can see the electricity line but not the hangers. That is because of the way the sun is shining.

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 has been the world's most slender arch bridge for 44 years. It needed 44 t of structural steel and 7 t of prestressing steel. The rise of the arch was 18% of the span.

Figure 1. Bolstadstraumen bridge is the world's most slender arch bridge.

A competing arch bridge with vertical hangers and a rise in the arch of 21.5% of the span needed 2.5 times more structural steel. Both bridges had a concrete slab spanning between the arches. With transverse beams in the tie the competing bridge would have needed more structural steel.

The influence lines and the geometry of the Bolstadstraumen Bridge can be found on p. 59.

## 2 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.

The force in the chords can be reduced by increasing the distance between them, but aesthetic considerations limit the rise of the arch.

In network arches some mainly axial forces can not be avoided. The optimal network arch takes these forces as efficiently as possible. The optimal

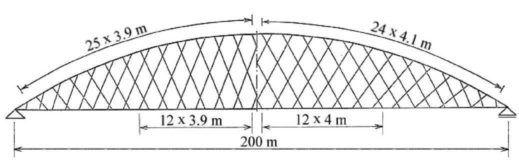


Figure 2. Skeleton lines for two network arches spanning 200 m. p. 8. (Tveit 1980).

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 compression in the arch is only around 3% greater than the tensile force in the tie. Arch and tie are closely connected by the hangers. Thus the arch can take a big buckling stress. All members make good use of high strength steels.

The arches can be made from universal columns or American wide flange beams that come pre-bent from the steel works. Since the arch only has compression, butt joints can be used. p. 12.

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. P. 39, 57 and 58. The hanger arrangement to the right in fig. 2 has a higher resistance to relaxation of hangers than the arrangement on the left.

Network arches are equally well suited for rail and road bridges. Where a steel tie is used in railway bridges, about 30% of the steel has been saved compared to arch bridges with vertical hangers. p. 35. If a concrete tie is used, around twice as much steel can be saved. p. 8, 31 and 93.

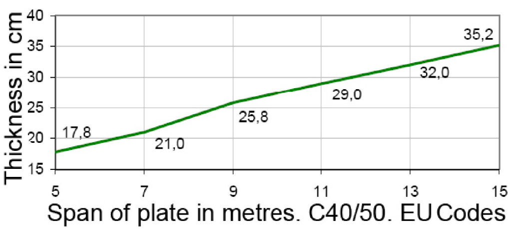


Figure 3. Necessary thickness of a concrete slab lane. (Teich and Wendelin 2001).

Where the tie is a concrete slab, the biggest bending stress can be found halfway between the two arches. p. 14. Thus we do not need a big longitudinal beam in the tie. We just need an edge beam for the prestressing cables, which must be strong enough to take the forces from the hangers. The prestressing cables between the ends of the arches shall be placed in the middle of the edge beam.

Figure 3. gives the necessary thickness of a concrete slab between arches. Higher concrete strength could give an even thinner slab. For slabs spanning over 10 m transverse prestressing should be considered. Should too big deflections occur, they could be counteracted by spanning fiber reinforced polymer strands under the slab.

## 3 AN OPTIMAL NETWORK ARCH

The bridge in fig. 4 is a bridge between two islands in northern Norway. The footpaths are placed outside the arches to reduce the bending in the concrete slab between the arches. The footpaths must have room for the machines that remove the snow.

The traffic is so little that we do not have to worry about fatigue in the hangers. Otherwise the bridge is designed according to the EU norms. The arches are universal columns that have been preshaped at the steel mill.

Two ways of fastening the windbracing are shown. If a box section had been used, the details would have been much more complicated and the outer dimensions of the arch would have been bigger.

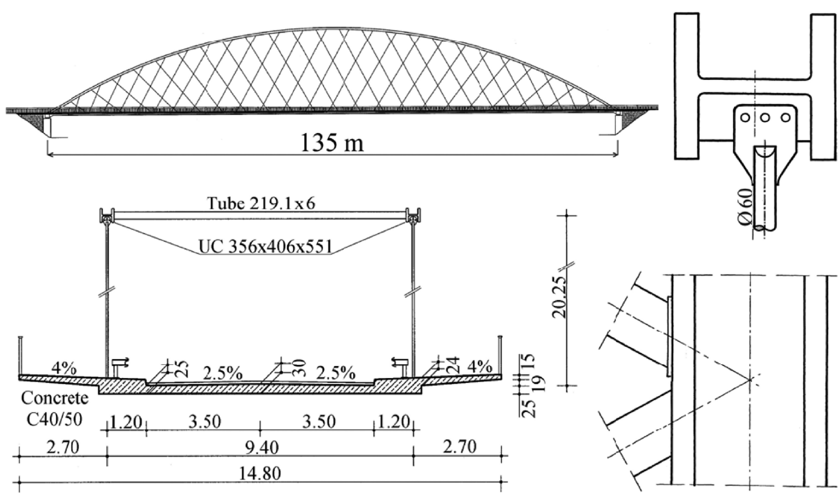


Figure 4. The Åkviksound network arch designed in by (Teich and Wendelin 2001).

In fig. 5 the steel weight per m2 of this network arch is compared to steel weights of German arch bridges with vertical hangers.

N indicates that there is no windbracing. S indicates that the arches slope toward each other. The spans and the year they were built are indicated.

The network arch tends to use less reinforcement in the tie than bridges that have steel beams under the concrete slab. This is remarkable because the bridges with vertical hangers have transverse and longitudinal steel beams in the tie. Furthermore the reinforcement in the network arch is less complicated.

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. The longitudinal steel beams have high tension. Therefore the slab on top needs a lot of reinforcement to keep the cracks small.

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

If the network arch is narrow, most of the reinforcement is decided by the area around the concentrated load. Little extra reinforcement is needed to get the loads to the edge beams.

Transverse beams in the tie concentrate the load on the edge beams. A slab gives a distributed load on the edge beams. Thus it leads to smaller bending moments in the chords.

The network arch uses only 33% of the structural steel used in the Calbe Bridge and 23% of the structural steel used in the Jerusalem bridge in Magdeburg.

When in doubt, (Teich and Wendelin 2001) usually adopted solutions that gave more steel. The steel weight in the Åkviksound network arch would have been smaller if it had the same rise in the arches as the other arch bridges in fig. 5.

As you all know, steel weight is not the only thing that matters. Let us look at other differences between arch bridges with vertical hangers and network arches of the Åkvik type.

Bridges with vertical hangers are bulkier. They have 2 to 8 times deeper chords. That gives less slender spans and makes the ramps longer, and branching out roads at the ends of the bridge is more difficult.

Where vertical hangers are used, welds tend to be 15 to 30 times longer. The details are more complicated and there is 3 to 7 times as much surface to protect.

Other concrete parts need much more maintenance than concrete slabs with a slight prestress. Erection is less expensive with a half to a quarter of the steel weight to erect. The light steel skeleton can be assembled on shore and be lifted into place. See later.

## 4 A METHOD OF ERECTION

The scaffolding for the network arch at Bolstadstraumen is shown in fig. 4. It was erected on piles in the sandy bottom of the river. After the concrete tie was cast, the arch was erected. Then the hangers were installed and tensioned till they carried the tie. Then the wooden scaffolding was removed.

Similar methods of erection can be used if the scaffolding would not be costly, for instance, for footbridges in towns and over rivers that have little water half the year. In these cases bridges with shorter spans would very often be more competitive.

## 5 TEMPORARY TIE

Figure 7 shows a temporary tie for the erection of network arches. Combined with arches and hangers it

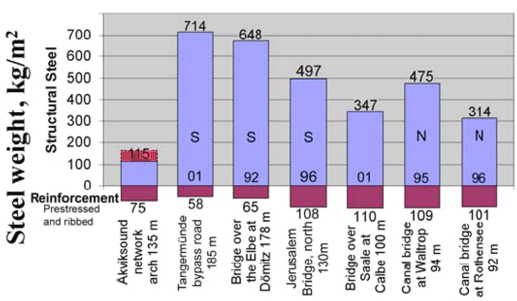


Figure 5. Steel weight per m$^2$ for various arch bridges.

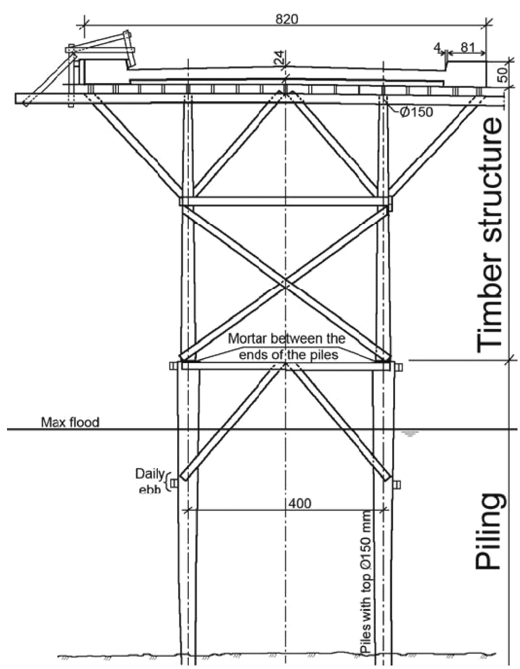


Figure 6. Scaffolding of the Bolstadstraumen network arch.

makes a stiff steel skeleton that can be moved. This temporary tie needs no corrosion protection. It can be produced on site, using high strength bolts.

This skeleton can be erected at one side of the river or fjord and pulled over by cables from a tower on the opposite side.

This is very appropriate for spans over rivers with very variable water levels, and in New Zealand where Maori tradition forbids touching the river. The steel skeleton can carry the casting of the concrete tie. p. 29k to 30a and p. 50a to 50b.

First the concrete is cast around the curved parts of the prestressing cables. That is at the ends of the tie. After that, a slight prestress 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.

The steel in the temporary chord can be reused in bridges of different network arches with various widths and lengths. The plywood plates in the formwork can be reused for many purposes.

The temporary tie should be considered in the unlikely event that the network arch needs to be taken down. The temporary tie could be put in place again. Then most of the concrete can be removed, before the remaining parts of the span are pulled over to the side-spans again.

## 6 REMOVAL OF TEMPORARY TIE

The removal of the temporary tie can be done using the wagon shown in fig. 8. p. 52 to 53a. The floor of the wagon has two extra long transverse beams that have been part of the temporary tie.

Four L-shaped beams with wheels on top have been fastened to the transverse beams before the platform has been lowered. The wagon can roll along the edge of the tie while the rest of the temporary tie is taken down.

## 7 THE SKODJE NETWORK ARCH

Figure 9 shows a suggestion for a network arch in Skodje in western Norway. p. 20 and 50a to 51. Very few ships will pass under the bridge so the low parts of the arch are allowed above the navigable parts of the fjord.

The parts of the arches that are under the lane can be floated in or erected from the side-spans. The structural steel above the lane, supplemented by a temporary lower chord, can be erected on side-spans. Then this steel skeleton can be floated across the fjord by means of a pontoon or a floating crane.

## 8 NETWORK ARCHES WITH CHORDS OF HIGH STRENGTH CONCRETE

Since concrete is good at taking compression, it would be a suitable material for arches in network arches. Steel rods can be used in the hangers.

The forerunners of the network arch were the Nielsen bridges. p. 54. (Nielsen 1929), (Nielsen 1932) Around 60 of these bridges was built between the two world wars. (Ostenfeld 76) Their arches were usually made of concrete. Today that would give too high scaffolding costs. Next to none of the hangers of the Nielsen bridges have broken in the roughly 70 years since they were built.

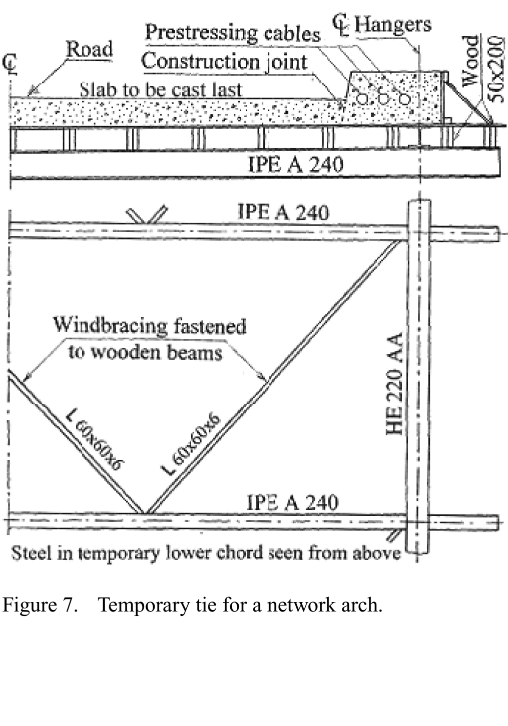


Figure 7. Temporary tie for a network arch.

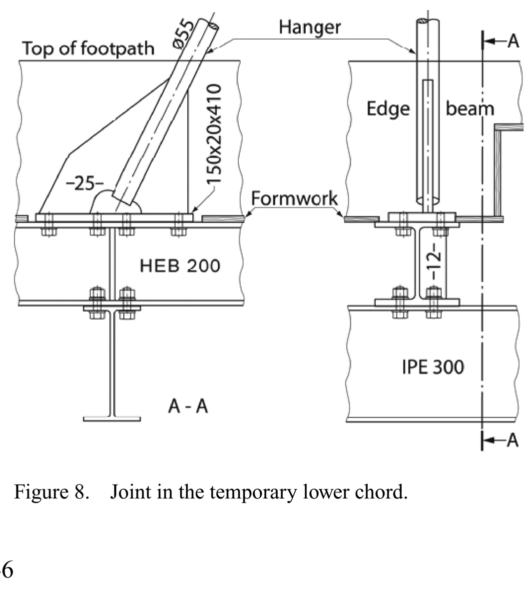


Figure 8. Joint in the temporary lower chord.

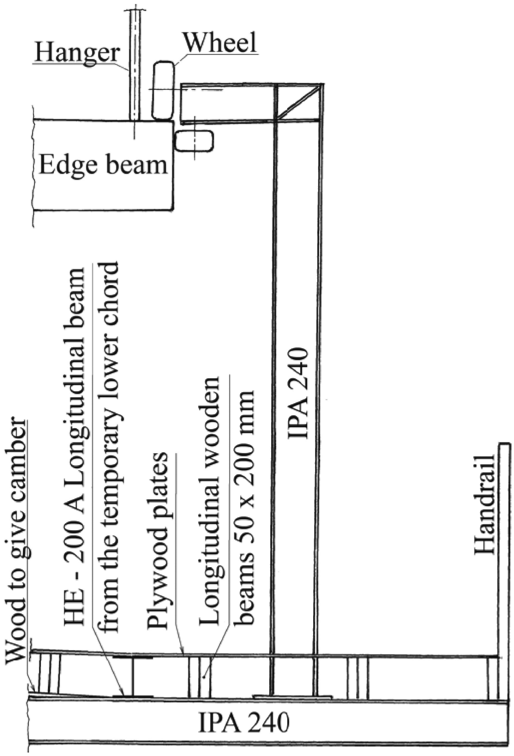


Figure 9. Wagon for removing the form and the temporary tie.

Network arches with chords of a high strength concrete can be used when many equal spans over 100 m are needed. They can be finished on the shore and be lifted out by big floating cranes. (Tveit 1980) See fig. 10.

## 9 STRENGTHENING OF NETWORK ARCHES ALREADY BUILT

It is never easy to strengthen an existing bridge. The network arch is no exception, but some things can be done. p. 50. An outside tensile member can strengthen the lower chord, but it will be difficult to fasten the tensile member at the ends.

If the lower chord is a concrete slab, it can be strengthened by transverse tension members under the slab. The tension members can be fastened to anchors glued to the outside edges of the slab.

The tension members could be stressed by ordinary tensioning or by a kind of wedge between the slab and the tension member. The tension members can be steel rods, wires or fibre reinforced polymer strands.

If the arch is an H-profile like in fig. 4, it can be strengthened by welding a steel plate on top of the arch. The plate will increase the bending capacity in the arch. The bending capacity in the lower chord will also increase, but not so much.

## 10 LIFTING BY BIG FLOATING CRANES

The Brandanger Bridge will be built in Norway in 2009. p. 94. The main span will be a network arch spanning 220 m. It will be built on shore and then lifted

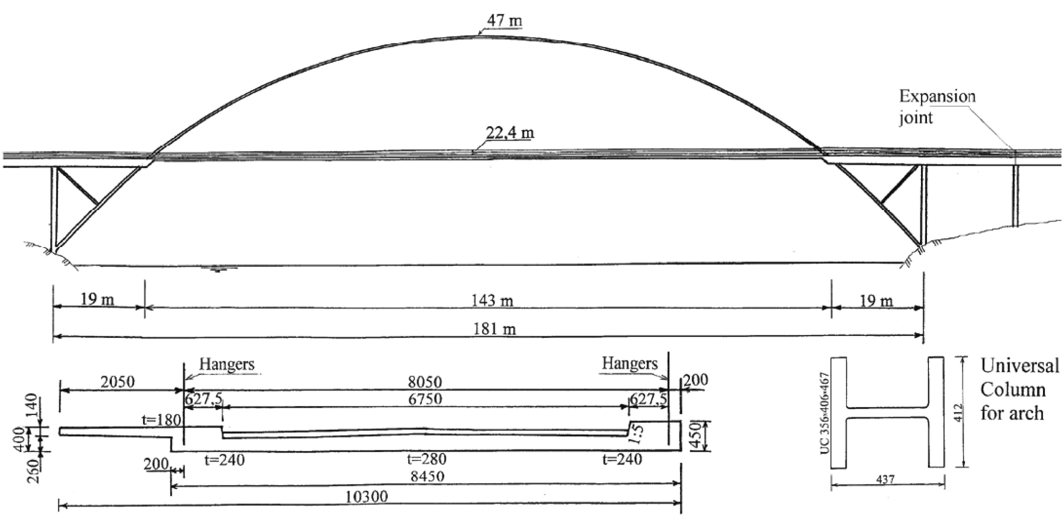


Figure 10. Network arch suggested at Skodje in western Norway. p. 20.

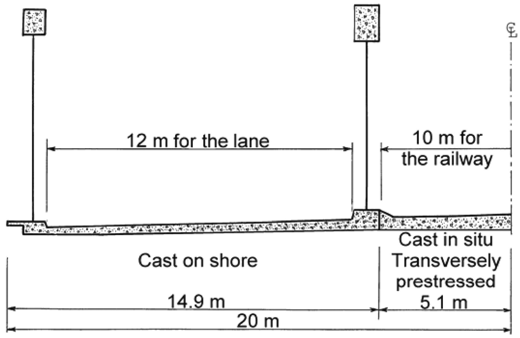


Figure 11. Cross-section of concrete network arch.

to the pillars by two floating cranes lifting over 800 tonnes each. It will be at least twice as slender as the Bolstadstraumen Bridge. (Larsen and Aas- Jakobsen 2006) and (Tveit 2006).

Floating cranes can lift up to 3000 tonnes. They can be used for lifting finished spans over 300 m. Concrete network arches with a cross-section like in fig. 9, spanning around 250 m, can be lifted in place before the slab under the railway is cast. p. 28.

## 11 WHY HAVE SO FEW NETWORK ARCHES BEEN BUILT?

Network arches have been built in the Czech Republic, Germany, Norway and USA. It has been decided to build more network arches in all these countries. The author has been wondering why so few network arches have been built.

The introduction of the optimal network arch would give extra work for bridge designers, and there is a general shortage of engineers that can be trusted with the design of a first network arch. Everybody has a lot of intriguing problems that they would rather study. In many cases the excuses for not using network arches are not valid.

Steel firms have little interest in bridges that need so little steel. The concrete firms would like to see more concrete. They do not favour having to cooperate closely.

The introduction of the optimal network arch would give extra work for bridge authorities. However, the author hopes that they will find the time and the courage to promote network arches. General conservatism might be the main reason why this promising type of bridge is not built.

## 12 CONCLUSION

Network arches need little materials. In network arches with less than 15 m between the arches, the tie can be a thin concrete slab. Compared to arch bridges with vertical hangers and steel beams in the tie, an optimal network arch normally saves over two thirds of the structural steel. Still both alternatives use nearly the same amount of reinforcement.

Optimal network arches can be very slim, which gives a pleasing appearance. In bridges where many equal spans are needed, the arches can be made from concrete. Spans up to 300 m can be finished on shore and floated to the pillars.

To some civil engineers the author's claims may seem exaggerated, but it would be stupid to exaggerate when the bare facts seems like an exaggeration.

Most of the network arches that have been built have permanent steel beams in the ties. The author appeals to all members of *fib*. Do not let the steel people highjack the network arch.

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