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How to Design Economical Network Arches

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Abstract. The network arch is an economical bridge type that can look good and needs 35 to 50 % less steel. Economical methods of erection using light steel skeletons can be found. The network arch is defined by having hangers that cross each other at least twice [1]. The arches are made of steel. When the distance between the arches is less than 20m, the author thinks that the tie should normally be made of concrete.

1. Introduction

After having worked on network arches for 63 years. Most of his ideas can be found on his website. [1] The author is happy to get this opportunity to present some of his ideas. The network arch is defined by having hangers that cross each other at least twice. The arches are made of steel. When the distance between the arches is less than 20m, the author thinks that the tie should normally be made of concrete. Network arches have been built in around 30 countries, which can be seen in figure 1.

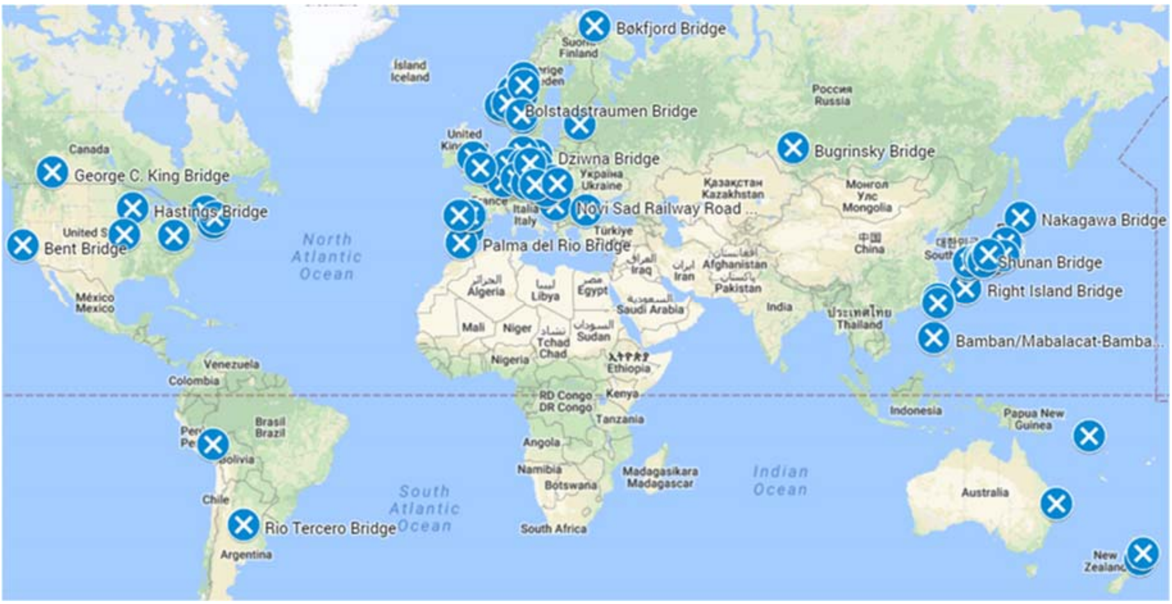

Figure 1. Map with most of the network arches in the world: www.tinyurl.com/nettverkbogekart

The saving in steel using network arches is illustrated by figure 2.

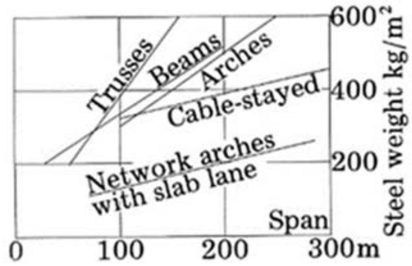

Figure 2. Steel weight of different bridge types according to Max Herzog and the author. [2][3].

2. A brief history

O. F. Nielsen [4] designed arch bridges with sloping hangers as shown in figure 3. This very much reduced the bending in the chords, because a load on the left hand of a span would activate the hangers sloping to the right, and thereby give a more even load on the arch. This would reduce the bending in the arch, which could be made slimmer.

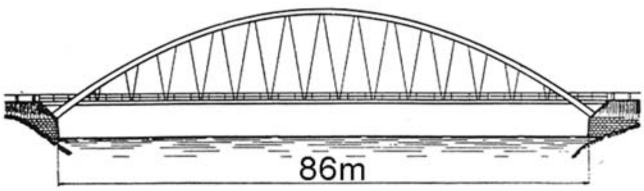

Figure 3. Nielsen bridge, built in Sweden in 1928

O. F. Nielsen never built bridges with crossing hangers, but he showed hangers crossing each other once in an application for a patent in 1926.

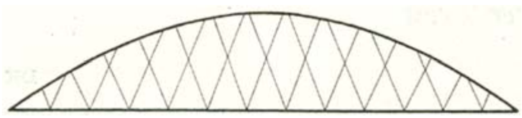

Figure 4. Drawing from O. F. Nielsen's patent application in 1926

He had two reasons for this. Little could be gained by crossing hangers with the small loads and the low strength of materials of those days. Using his method of calculation of the spans, crossing hangers would have made the calculations very complicated.

Around 30 of O. F. Nielsen's arch bridges were built in Sweden between the two world wars. Professor Arne Selberg of NTH in Trondheim thought that maybe this bridge type should be built in Norway. Thus, the author's master's thesis dealt with the calculation of O. F. Nielsen's bridge type. During his work with his master's thesis, the author came to think of a bridge type with hangers that cross each other more than twice. See figure 5. The hangers distribute the load over the arch in a good way.

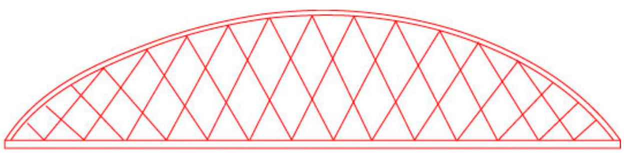

Figure 5. Network arch suggested in the authors master thesis in 1951

Later the author called this bridge type a network arch. Up to 1959 he used model tests in much of his work on network arches.

3. Aesthetic

Network arches are slim. That is good, because if you look at a landscape that has a bridge, you can see either the countryside or the bridge. It is best if you can see both at the same time.

A span looks best if the height of the arch is 0.15 to 0.16 times the span. A higher rise usually cost less. The span looks stronger if the lower chord has a rise of 0.01 to 0.02 times the span. It costs less if the arches are vertical, but it tends to look better if the arches slope towards each other. Architects and civil engineers should cooperate in the design of network arches, but the author thinks that the engineer should normally be in the driver's seat.

4. Parts and shapes of network arches

Here the author will explain the different parts of the network arch.

4.1. Curvature of the arches

The curvature of the arches should be much as indicated in Figure 6. With this shape of the arch, increased cross sections are shorter.

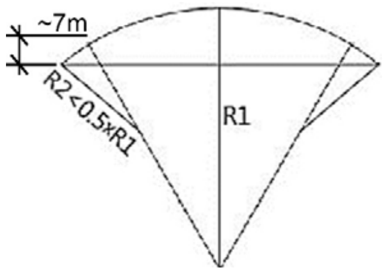

Figure 6. Curvature of the arch

4.2. Placing of hangers in the arch

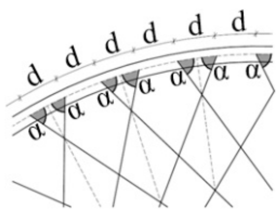

Figure 7. Angles between hangers and distribution of hangers along the arch [5].

The hangers can have many forms. Hangers much like those indicated in figure 8 can be recommended. If hangers are damaged, they can be replaced quickly. When the tie is made of concrete, steel wires with adjustment mechanism as in the Steinkjer network arch should be considered. If the hangers are tied to each other where they pass each other, they will have less tendency to vibrate. Broken hangers in a network arch are less likely to make a span collapse, because hangers that are near to each other at the tie will be spread out at the arch.

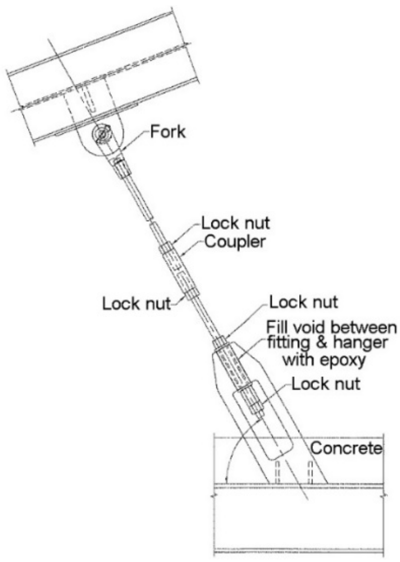

Figure 8. Adjustable hangers

4.3. Lower chord of network arches

The lower chords are normally made of steel. However, the author prefers them to be concrete plates. Transversal and longitudinal bending in concrete plates are usually of the same magnitude. Thus, the lower chords can be slim. The temporary form on which the concrete plates are cast can be used in spans of varying widths and lengths. See figure 9.

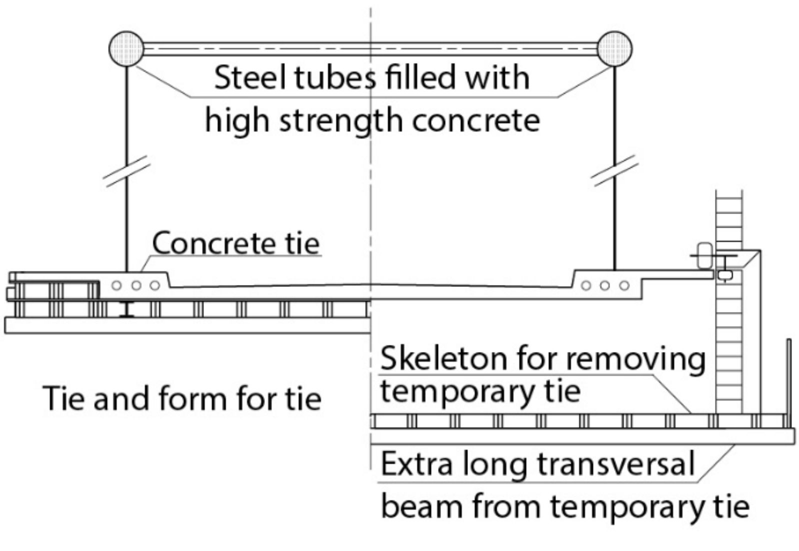

Figure 9. Form for casting of cross-section and removal of its form

If the deflection of the concrete plate becomes too big, it can be counteracted by fibre-reinforced polymer threads under the plate. See figure 10. The threads can be fastened to holes used in the erection of the bridge. The threads can be tightened by shortening the ropes under the middle of the plate. Snapping of the threads under the bridge must be avoided. The height and the place of the stools can be altered during the lifetime of the bridge.

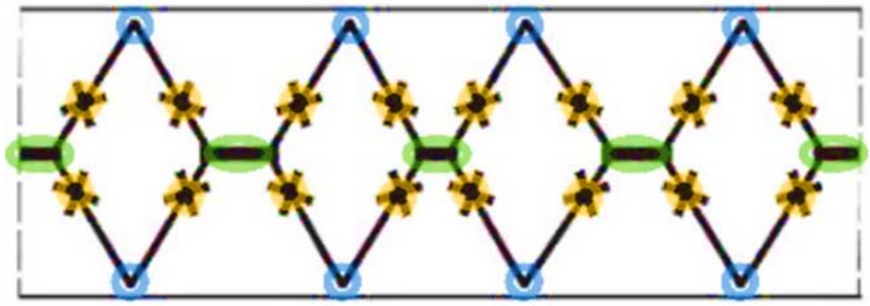

Figure 10. Threads under the tie. Blue for fastening threads. Yellow for stools. Green for tensioning.

5. Erection

Network arches can be erected in many ways as described in Stephan Teich's Ph.D. thesis [8]. Figure 9 shows the form for casting and removal of the form for the lower chord if the removal cannot be done from a barge.

According to Bao-chun Chen et. al. [9], tubular arches can be pumped full of high strength concrete after a light steel skeleton has been brought to the pillars. When the concrete has sufficient strength, the tie is cast. First the concrete between the ends of the arches is cast. Then the edge beams are cast. The casting starts from both ends to avoid relaxation of hangers. At the end, the lane is cast. Afterwards the temporary lower chord is removed. It can be used again and again.

6. Examples of network arches

6.1. Steinkjer Bridge, Norway

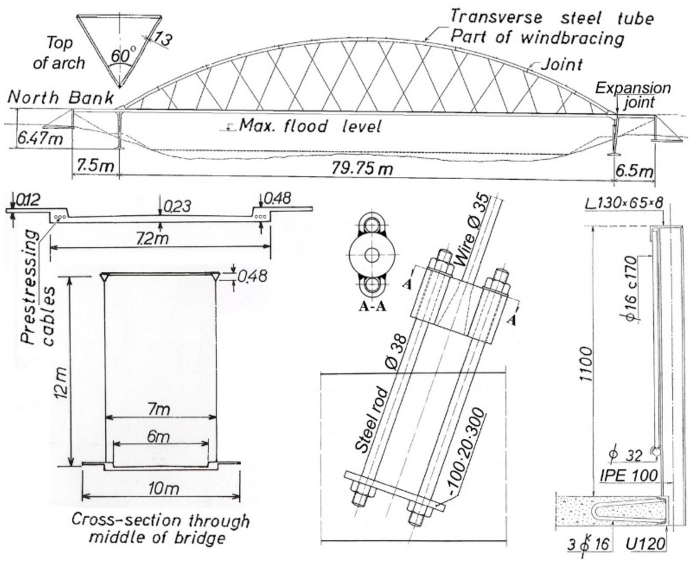

Figure 11. The Steinkjer network arch was opened in Norway in June 1963 [6][7].

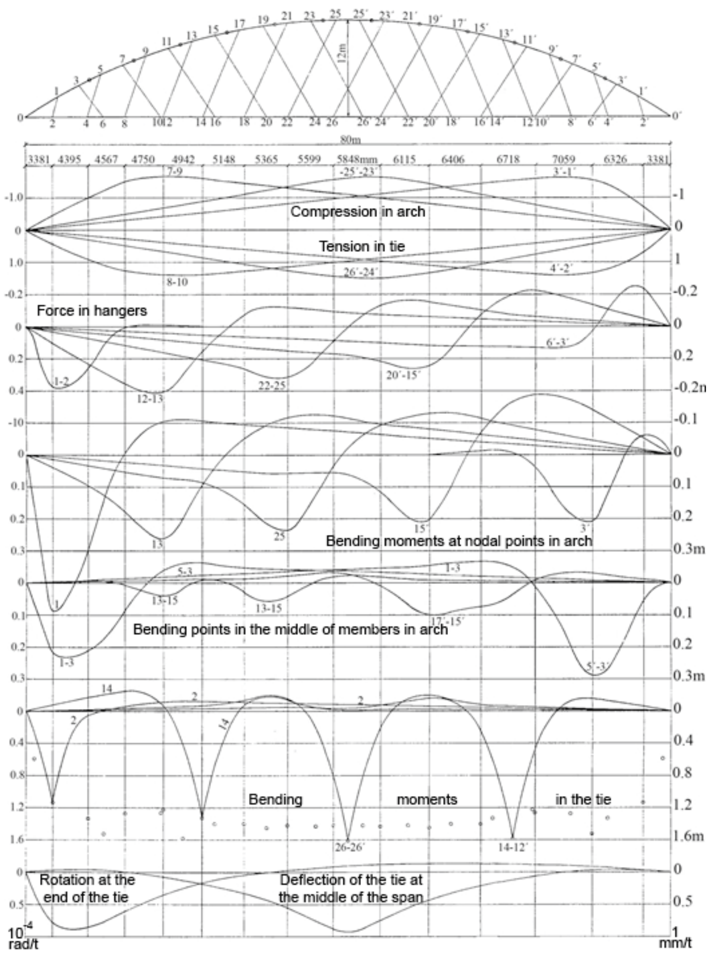

Figure 12. Influence lines of the network arch at Steinkjer. Examples of influence lines of other network arches can be found in The Network Arch [1] page 57 to 58.

6.2. Providence Bridge in Rhode Island, USA

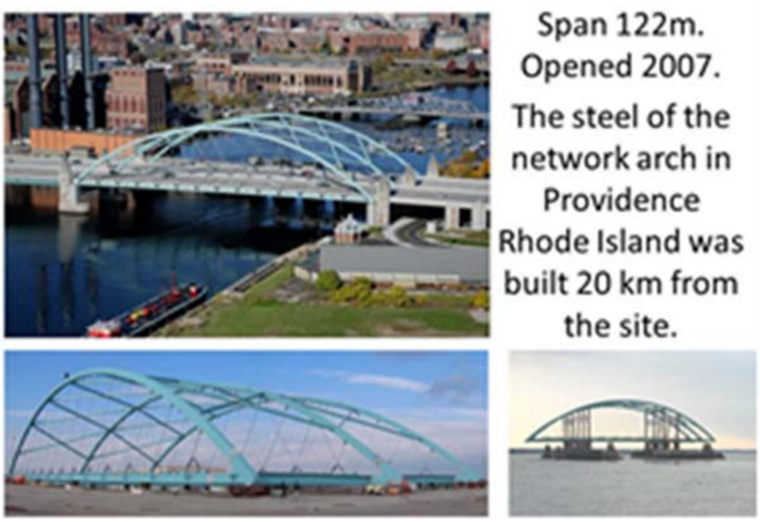

Figure 13. Providence Bridge in Rhode Island. Opened in 2007.

The bridge was the first network arch that was built in the USA. It had five lanes in each direction. The photos above show how the steel skeleton was built on a quay 20 km from the site and was floated to the pillars. The tide was used for putting the span on the pillars [10].

6.3. Blennerhassett Bridge in West Virginia, USA

Figure 14. Blennerhasset Bridge was opened in 2008. Span 268 m.

During the building of the bridge the river had to be open for traffic. This made the erection extra difficult.

G. Wollmann et. al. [11] found that the use of sloping, instead of vertical hangers, reduced the deflection due to the moving loads by a factor of 10.91. The bending moments in the arch were reduced by a factor of 3.65. Longitudinal moments in the tie were reduced by a factor of 5.75.

6.4. Shin Hamadera Bridge in Sakai in Japan

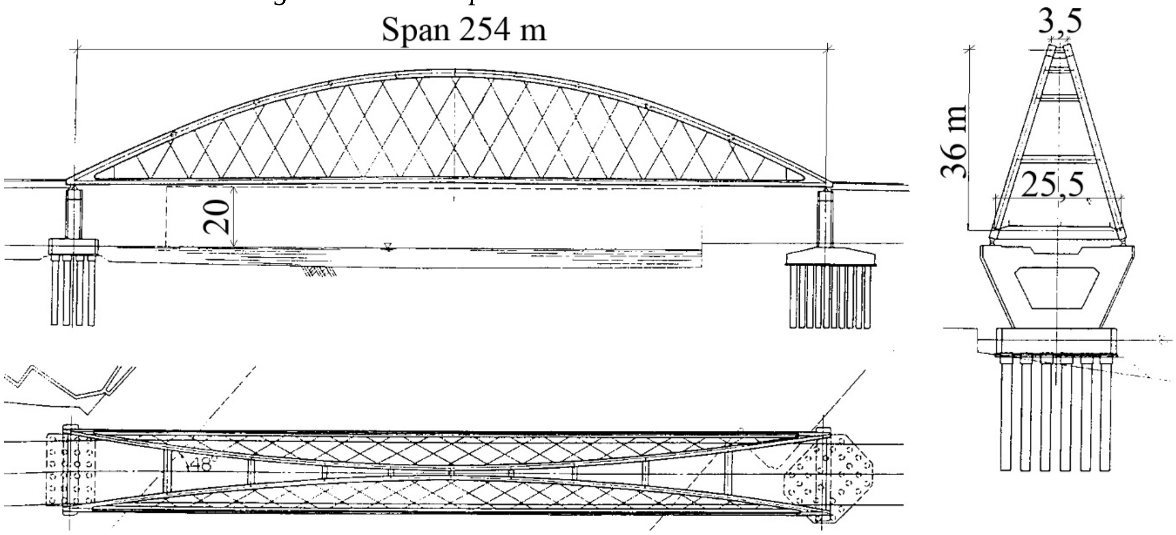

Figure 15. Network arch built in Japan in 1991. Span 254 m.

The main span of the Shin Hamadera Bridge was finished on a quay and was lifted onto the pillars by two big floating cranes [12].

6.5. Brandanger Bridge in western Norway

Figure 16. The 220m span of the Brandanger Bridge, moved to the pillars by big floating cranes.

The Brandanger Bridge was built over a sound in western Norway. It is the slenderest arch bridge in the world [13].

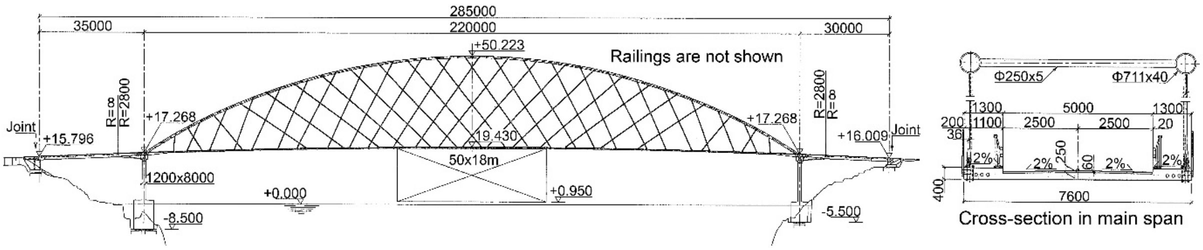

Figure 17. Overview and cross-section of the Brandanger Bridge.

There are little current and few boats in the Brandanger Sound. Much money would have been saved if the pillars were replaced by boxes at both ends of the bridge. The boxes would be anchored to the very good rock and could be used for storage.

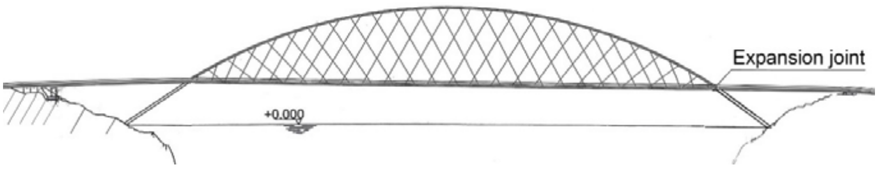

Figure 18. A possible economical design of the Brandanger Bridge.

6.6. Possible design of a span across a canal when heavy cranes are not available

The network arch is a light bridge structure that can be lifted in place by other means than heavy cranes.

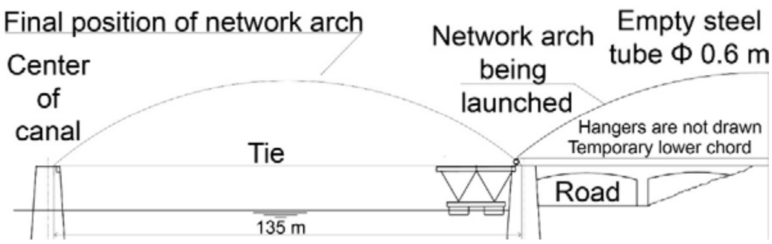

Figure 19. Economical design of a network arch over a canal [14].

In this example you first build the steel skeleton on the shore. Then the skeleton is rolled onto a pontoon that is pulled onto the central pillar. Then the tubular arches are filled with concrete and the lower chord is cast.

6.7. Bugrinsky Bridge over Ob in Sibir, Russia

Figure 20. Network arch over Ob in Siberia. Span 380m.

The road bridge in figure 20 was opened by president Putin [15] in 2014. He was pleased with the bridge. It is the longest network arch in the world. Those who designed the bridge got the idea from a lecture that the author gave in Moscow in 2007. Under the bridge there is a crack in the crust of the earth. Thus, the distance between the pillars will be changing over the years.

7. Advantages of network arches

- A well-designed network arch is likely to remain the world’s slenderest tied arch bridge.
- The slim chords look nice, and do not hide the landscape or cityscape behind them.
- Network arches are equally well suited for road and rail bridges.
- The network arch can have small deflections and small end tangents. This makes it suitable for high-speed railways.
- The slim tie is an advantage when the traffic on the bridge is lifted up to let other traffic pass under it.
- The slim ties of network arches can lead to smaller and shorter ramps leading up to the bridge.
- Lightness and vertical reactions give savings in the substructure.
- Network arches are not sensitive to uneven settlements in the foundations.
- All members efficiently carry forces that cannot be avoided in any simply supported beam.
- Tension is predominant in tie and hangers. All hangers will have the same cross-section.
- Network arches use very little steel. High strength steels are well utilized.
- Tie and hangers give the arch good support and high buckling strength in the plane of the arch.
- If the bridge has around 20m between the planes of the arches, the tie can be a concrete slab.
- Concrete ties should have small edge beams with longitudinal prestressing cables.
- Network arches have small bending moments in the chords.

- For daily loads there will be few transversal cracks in the concrete. This makes concrete in the slab between the arches extra durable.
- Network arches have small surfaces. Thus, they need little corrosion protection.
- Most concrete parts need more maintenance than a concrete slab with a slight prestress.
- Efficient methods of erection are available.
- Erection can be done using a temporary lower chord which is combined with the structural steel. It can have enough strength and stiffness to carry the casting of the concrete tie.
- If things go well, the network arch can save 40 % of the cost and 70 % of the structural steel.
- According to Ted Zoli and Ryan Woodward [16], the network arch is a robust structure.
- 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 some other bridge types.
- A high percentage of the cost will be labour, and a low percentage will be materials. This is good for countries that have well qualified manpower.
- The network arch has good resistance to earthquakes, because the strength/weight ratio is high. The prestressing cables in the edge beams give good resistance to horizontal vibrations.

8. Conclusions

Network arch bridges have been built in around 30 countries. Many of them have been built in Japan, Germany, USA and Norway. The network arch is a good-looking and structurally strong bridge that can save a lot of money, mainly because the bridge needs less steel. The low vibrations in the bridge is especially advantageous when network arches are used for railway bridges. If the span is less than 200m, then the tie should normally be made of concrete with longitudinal prestressing cables between the ends of the arches. When spans are over 80m, the arch should often be made of steel tubes filled with high strength concrete. Then a light steel skeleton can be lifted to the pillars before the tie is cast.

Some of the facts presented in this paper might seem like exaggerations. They are not. It would be silly to exaggerate when the bare facts seem like an exaggeration. Conservatism is part of the reason why network arches are not built in larger numbers.

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