Arch bridges
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NETWORK ARCHES FOR ROAD BRIDGES

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Abstract. *Network arches have hangers that cross each other at least twice. In optimal network arches the tie is a concrete slab between edge beams with longitudinal prestressing cables. There are no transversal beams. For road bridges spanning up to 250 m and double track railway bridges spanning up to 100 m, the arches should usually be universal columns or American wide flange beams.*

.....The details of an optimal network arch are simple, light and highly repetitive. The welds are short. The network arch looks attractive and is likely to remain the world's most slender arch bridge. It has very low bending moments. Tension is predominant. The arch has good lateral support. Thus the network arch makes good use of high strength steels.

The lower chord is usually a concrete slab spanning between edge beams under the arches. The tensile force in the lower chord is taken by prestressing cables in the edge beams. The footpaths should normally be outside of the arches. Where many spans are required, network arches can be made on shore from high strength concrete and be floated in place.

During erection, the arch and hangers, supplemented by a light temporary lower chord, can be moved when lifted at or near the ends of the arches. When in place, this light steel skeleton has enough strength and stiffness to support the casting of the concrete tie.

This steel skeleton can be erected on the side spans and be floated to the other bank. It can also be erected on ice and be lifted onto the pillars. If it is erected on land, it can be floated to the pillars on pontoons. In wide rivers and costal areas it can be put in place by big floating cranes. Big floating cranes can lift finished network arches spanning up to 300 m.

.....Compared to other bridges, the optimal network arch saves up to 70 % of the steel. Steel firms are usually not interested in using so little steel. The introduction of the network arch would create extra work for bridge authorities, but it is up to them to promote it. General conservatism might be the main reason if this promising type of bridge is not introduced.

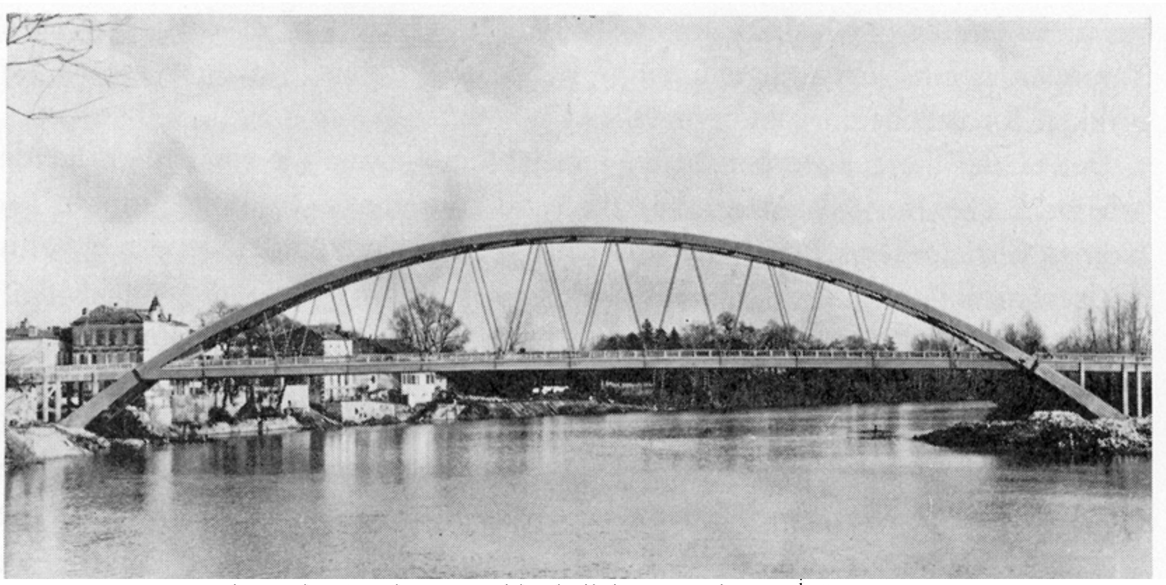


Fig.1. The Castelmoron Bridge built in France in 1933[i]. Span 154 m.

1 INTRODUCTION

The senior author came upon the idea of the network arch when he was writing his graduation thesis at the Technical University of Trondheim, Norway in 1955. Since then it has been his main field of research. Most of the results of his research on network arches can be found at[ii]. That home page will be updated at irregular intervals.

The graduation thesis started from O. F. Nielsen's bridges with inclined hangers. Fig. 1 shows the one with the longest span. More than 60 bridges of this type were built in Sweden between the two World Wars. The slope of the hangers probably gave enough redistribution of loads to make load on part of the span less decisive than the full load on the span.

To simplify the calculations all the hangers of Nielsen's bridges had to have the same slope. With higher loads and stronger materials it is economic to give the hangers a smaller angle with the horizon. This leads to hangers that cross each other.

The network arch in fig. 2 can be seen as a simply supported beam with a tensile and a compressive flange. The hangers are the web. Most of the shear force is taken by the vertical component of the force in the arch. The axial forces in the tensile and the compressive flanges are inversely proportional to the distance between them.

In tied arches, aesthetic reasons limit the distance between the arch and the tie. Thus saving of materials depends mainly on whether or not a design gives light chords and a light web. The hangers distribute the load between the chords in such a way that there is very little bending as long as all, or all but a few, hangers are in tension.

The network arch is an efficient structure for 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.

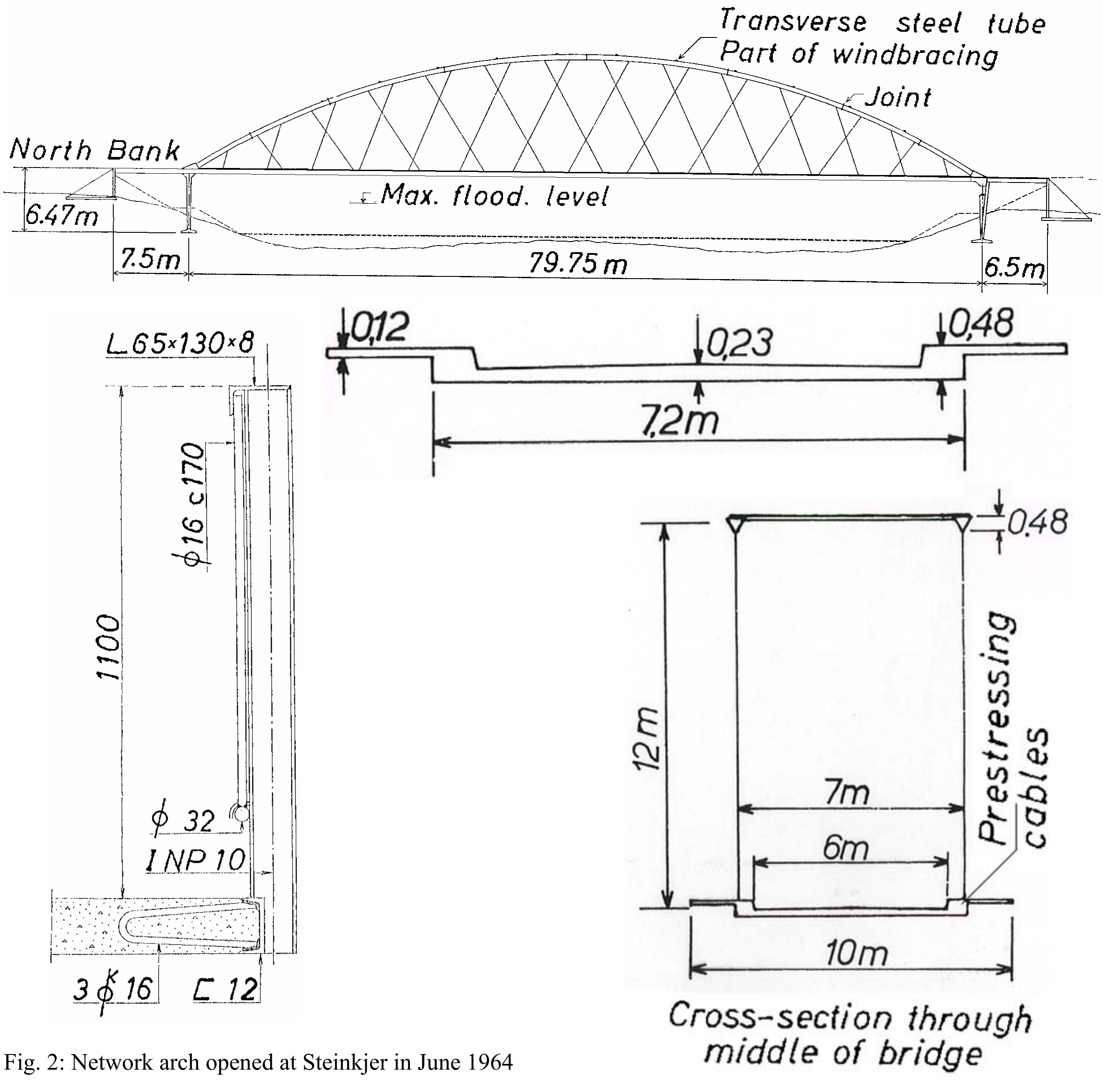


Fig. 2: Network arch opened at Steinkjer in June 1964

Every part of the structure makes good use of high strength steel. Because of a high strength to weight ratio, the network arch is suitable for seismic regions.

The optimal network arch seems to be the most competitive network arch. A near optimal network arch was built at Steinkjer in Norway [ii,iii,iv]. See figs. 2 and 3. In the author's opinion the following traits should be characteristic of the optimal network arch:

The upper nodes of the hangers should be placed equidistantly along the arch. The members between the last node and the end of the bridge can be a little longer than the other members. If the last member of the arch is made a little steeper, this can give a smaller bending moment at the end of a side span attached to the network arch. See the span at the north bank in fig. 2. If universal columns are used in the arches[v,vi], the lower end of the wind portal should have a steel plate on top of the arch. The cavity under this steel plate should be filled with concrete.

The tie has a concrete slab spanning between the planes of the arches. The footpaths are often placed outside the arches. The biggest bending moment in the tie is found in the middle of the slab between the arches. If high strength concrete is used, the distance between the arches can be more than 16 m. For slabs spanning more than 12 m partial or full transverse prestressing should be considered.

Fig. 3. Network arch at Steinkjer, Norway

One reason for the low cost of upkeep of optimal network arches is the small steel surfaces. Nearly all of them are above the road level. In the Steinkjer and the Bolstadstraumen bridges the arches had a triangular cross-section. See figs. 2 to 4. The triangular arches look good, but cost more than the universal columns and American wide flange beams. They also led to a costly wind bracing. The triangular arches are not optimal. Still the bridges in figs. 2 to 4 were built because they were less costly than competing alternatives. The Bolstadstraumen Bridge has been the world's most slender arch bridge for 40 years.

Fig. 4. Bolstadstraumen Bridge in Western Norway was opened in December 1963. Span 84 m.

3. Optimal arrangement of hangers

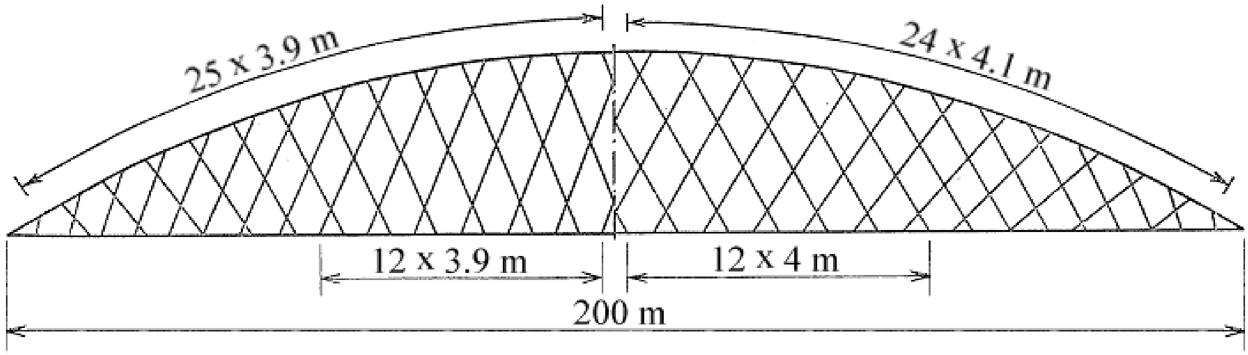


Fig. 5. Hanger arrangements for two different ratios of permanent load to live load[v].

The optimal arrangement of hangers will depend on many factors. Important considerations are the ratio of live load to permanent load, intensity of evenly distributed live load, magnitude of concentrated live load, form of arch, slenderness of the arch and tie, structural codes, etc. In the present paper it has been assumed that most of the arch is part of a circle, because this makes fabrication easy. Compared to the parabolic arch the constant curvature gives a more constant axial force in the middle portion of the arch and contributes to even maximum bending moments in the chords.

The arch is normally part of a circle. A reduced radius of curvature near the ends of the arch gives a shorter wind portal and very even axial force in the arch. See [v]. It would also be an advantage if a side-span were attached to the end of the arch as shown at the north end of the bridge in fig. 2.

Fig. 5 shows two hanger arrangements that are thought to be near the optimal. The geometry on the right was used in the Norwegian Åkviksound Bridge [ii,vii]. The geometry on the left was used in a network arch where the ratio of live load to dead load was smaller. When live loads increase and high strength concretes make the ties lighter, the slopes of hangers shown on the right are more likely to be used because they give the hangers a higher resistance to relaxation.

Hangers along the arch should be placed equidistantly. This arrangement gives the least bending due to local curvature of the arch when the span is fully loaded. Two hangers at each nodal point would give more bending in the arch due to local curvature and less efficient support of the arch in buckling. All hangers should have the same cross-section. With careful choice of the slope of the hangers, the force in the hangers can become surprisingly even.

In the network arches in figs. 2 to 4 there is a constant difference in slope in all hangers next to one another. These hanger arrangements give very even maximum forces in all hangers. Many other hanger arrangements do so too. It is difficult to decide what hanger arrangement is best. They all give reasonable results.

The hanger arrangement in fig. 5 gives extra resistance to the relaxation of hangers. This is often an advantage when a temporary lower chord is used during erection. It makes it easier to avoid problems due to relaxation of hangers when the concrete edge beam is cast. Constant slope in the hangers gives considerable variation in the hanger forces and the distance between the nodes in the arch. This is not optimal.

When some hangers relax, due to loading on one side of the span, the distance between points of support doubles and bending due to local curvature increases. Furthermore there is considerable increase in the bending moments in the chords when only one set of hangers connect the chords in parts of the span. Maximum stresses do not necessarily occur, because load cases that make hangers relax do not give maximum axial force in the arch.

A lot of calculations can be avoided by making the slope of the hangers so small that it is easy to prove that the load on the whole span decides the dimensions at every point in the arch. [ii] pp. 26 to 30.

Many hangers will increase the cost of labour. This increase will, however, be moderate since all the hangers have the same cross section and hanger details are simple and all alike. The repetitions tend to reduce labour costs. Many hangers also mean thinner hangers and lighter equipment for mounting and adjusting them.

An increased number of hangers gives lighter spans because it results in less bending in the chords and less local shear force at the lower end of the hangers. Many hangers go well with the slender single-rolled H-sections for the arches.

More hangers might lead to a lighter temporary lower chord if such a chord is used for erecting the span. Most hangers that are adjacent at the deck are well spaced at the arch. Thus, the network arch is less sensitive to hangers breaking than the usual tied arch.

The hangers nearest to the ends of the arch often have smaller maximum forces than the other hangers. Increasing the distance between the end of the span and the nearest upper node of a hanger can to some extent counteract this phenomenon. The first hanger in the tie should normally be sloping away from the end of the span as shown in figs. 2 and 5.

Hanger distances in the tie should be varied in order to obtain nearly the same maximum force in all hangers. It is best to avoid long distances between nodal points, because the greatest longitudinal bending moment in the tie often occurs where there is a long distance between nodal points. Since the longitudinal bending moments in the tie is small, this is not very important.

4. Network arches made exclusively from concrete

Until 1950 nearly all arch bridges with inclined hangers had concrete arches. This made sense because concrete is suitable for taking the compression that is predominant in the arch. Since then most arches of this kind have been made of steel. This has kept the scaffolding costs down and has simplified the erection.

Where many equal spans are needed, it might be economical to use concrete in the arches. High strength concrete is efficient at carrying large compressive forces in stocky members. To keep the cost of formwork down, the spans can be cast on shore and be floated to the piers, [ii] pp. 40 to 44. For long bridges this arrangement would have these advantages: Low weight and a high degree of prefabrication which would give low labour cost and good control of workmanship. The spans could be lifted in place by big floating cranes or by pontoons designed for the purpose.

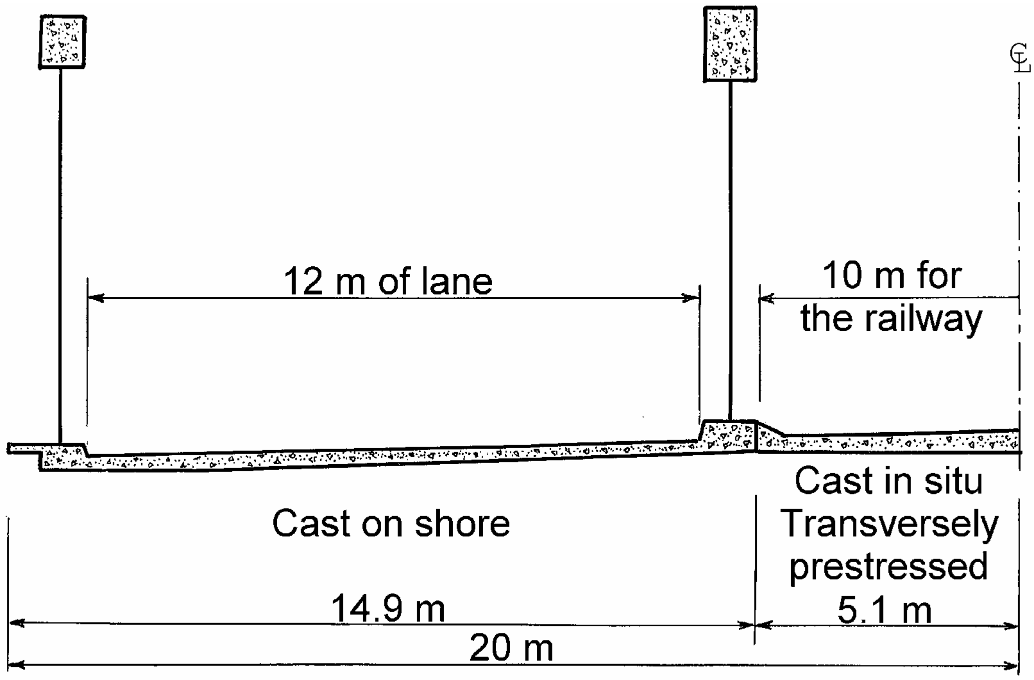
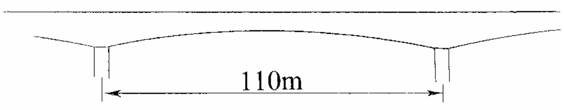
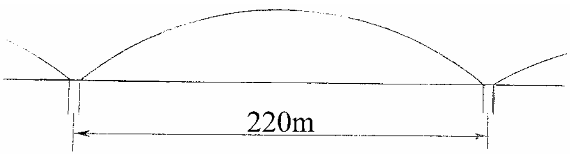


Fig. 6. Half cross-section of a network arch made exclusively from concrete.

COMPARISON BETWEEN THE BEAM AND NETWORK ARCH ALTERNATIVES FOR THE WEST BRIDGE IN THE GREAT BELT LINK. [ii] p. 43





Max. weight of beam elem.	5800t	Max. weight of arch to be moved	4000t
Weight of concrete per m:	100%	Weight of concrete per m:	45-55%
Weight of reinforcement per m:	100%	Weight of reinforcement per m:	50-75%
Bridge piers per m:	1/110	Bridge piers per m	1/220
Forces on bridge pillars per m:	100%	Forces on bridge pillars per m:	45-55%
Cylinder strength of concrete:	55MPa	Cylinder strength of concrete in tie:	55-65MPa
		Concrete strength in arches:	:80-90MPa
Price of substructure:	100%	Price of substructure:	50-75%
Price of superstructure:	100%	Price of superstructure:	60-80%

In this contribution “t” means metric tons.

Savings in price between 20% and 35%

4 ERECTION OF OPTIMAL NETWORK ARCHES

The tie of the two Norwegian network arches was cast on timber structures resting on piles in the river bed[iii]. Then the arch and hangers were erected. The hangers were cables. They were tightened with care till they carried the concrete deck.

The most promising method of erection uses a temporary lower chord that supplements the arch and hangers and has enough strength and stiffness to carry the concrete tie while it is cast. The same temporary lower chord can be used for many bridges of varying widths and spans.

5 OTHER NETWORK ARCHES

The Fehmarn Sound Bridge[ix] is a combined road and rail bridge to the island Fehmarn north of Germany. [ii] pp. 17 to 19. Professor Masao Naruoka saw model tests on the Fehmarn Sound Bridge in TH-Hannover in 1960. Naruoka[x] took the idea to Japan where it has been flourishing. xi, xii, xiii, xiv.

The longest Japanese network arch so far is the Shinhamadera Bridge[xiv]. See fig. 7. The Japanese call these bridges “Nielsen-Lohse bridges”. They might not know that O. F. Nielsen never crossed the hangers in the bridges that he built[ii,xv]. In his bridges the hangers were supposed to relax due to live loads.

Most of the Japanese network arches have ties where the hangers are fastened to the ends of transversal beams. Thus the distance between the upper ends of the hangers is uneven. About half of them have arches that slope towards each other. That looks nice, and the forces in the wind bracing and the wind-portal are reduced. The cost of the spans increases considerably because the span and the steel weight of the transverse beams in the lower chord go up.

A network arch[xvi] is being built in Providence, Rhode Island, USA. It is ~47 m wide and has a span of 120 m. Thus the tie has to have steel beams.

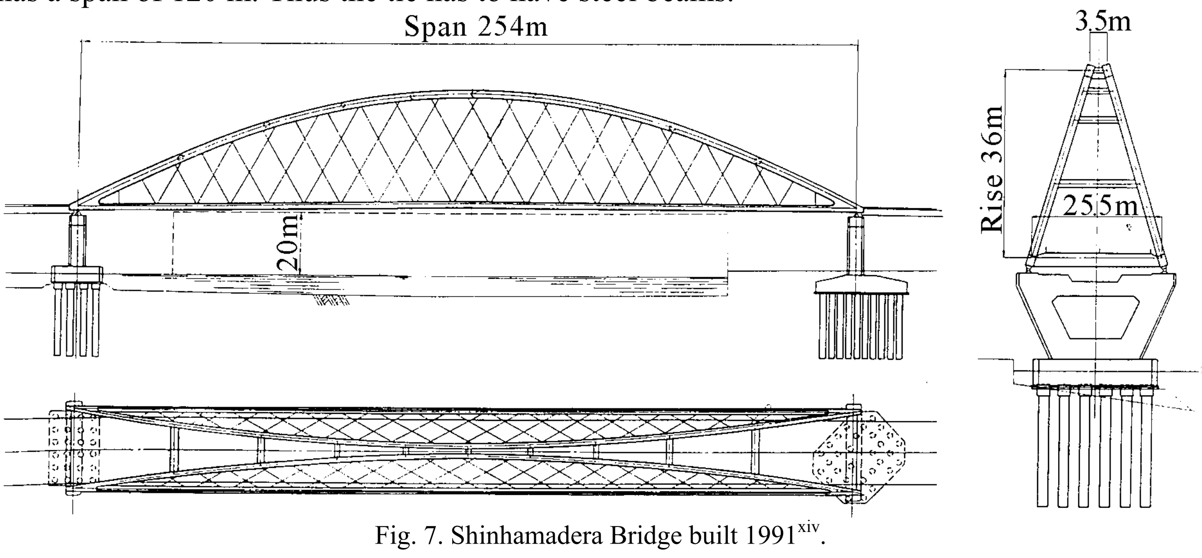


Fig. 7. Shinhamadera Bridge built 1991[xiv].

6 THE FUTURE OF NETWORK ARCHES

Predictions are difficult, especially about the future. Network arches will be used where structures above the lane can be accepted. This is often where traffic shall pass under the tie, for instance in bridges between islands and over rivers and canals. Then erection by means of pontoons and/or floating cranes should be considered.

When the design has been tested, it is likely that the network arches will preferably be used where the foundations will be costly. Then it pays to use longer spans, and the network arches compete extra well because their cost per m increases more slowly with length than the cost in other types of bridges. Thus the bridges with network arches will have longer spans and fewer intermediate foundations.

In bridges with one main span the length of the span will be bigger to make the abutments less costly. This depends on the availability of efficient methods of erection. In coastal areas where big floating cranes are available, the optimal length of spans will probably be longer. Moving completely finished spans of 250 m presents no serious difficulty for big floating cranes.

In developing countries where funds are limited and the traffic is growing fast it might be rational to build foundations for two parallel spans. The second span could be put in place when a higher volume of traffic asks for it.

Where many equal spans are called for, network arches made of high strength concrete should be considered. The materials will be inexpensive, and the formwork and scaffolding can then be divided between many spans. In bridges with few spans steel arches will probably be more competitive.

7 CONCLUSION

The two Norwegian network arches were built because they were less costly than competing alternatives. Network arches with arches made from rolled H-profiles will be even less costly.

It is straightforward to make the arch part of a circle, but a reduced radius of curvature at the wind portal might be advantageous. Network arches should have many hangers because that reduces the bending in the chords.

All hangers should have the same cross-section and nearly the same decisive hanger force. Hanger distances in the tie should be chosen to avoid this. The hangers slope with the horizontal greatly influences the hanger's axial force and their tendency to relax.

No load should lead to the relaxation of many hangers because this could lead to unacceptable increase of the bending moments in the arches. To steep hangers should normally be avoided, even if the structural strength is in order. It is a lot of work to examine all the relevant load cases that makes hangers relax.

For almost 50 years the senior author and a multitude of his students have been improving the design network arches. Future design and building of more network arches will probably lead to more improvements, but it would be a shame if improvements made till now were not utilized.

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