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REDUCE COSTS BY BUILDING OPTIMAL NETWORK ARCHES

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Abstract *Optimal network arches are arch bridges with inclined hangers. Some of the hangers cross each other at least twice. The tie is a concrete slab with partial longitudinal prestress. The transversal bending in the slab is usually much grater than the longitudinal bending. Thus the main purpose of the edge beam is to accommodate the hanger forces and the longitudinal prestressing cables.*

Network arches act very much like trusses on top of one another as long as no, or only a few, hangers relax. They have little bending in the tie and in the arches. To avoid extensive relaxation of hangers, the hangers should not be too steep. The bending moments due to concentrated loads will increase with reduced steepness of the hangers. [i]Page 67 and 68.

The optimal network arch has slim good looks. For moderate spans the arches should be universal columns or American wide flange beams. Optimal network arches make good use of high strength steel. This is because tension is predominant in hangers and tie and there is little slenderness in the arch. Compared with conventional bridges, the network arch usually requires less than half the steel. [i]Pages 8,13 and 31.

Efficient methods of erection make the network arch an economical alternative. The structural steel and a temporary tie make a light and stiff steel skeleton that can be moved. The permanent concrete tie can be cast when the spans are in place. In inland rivers the steel skeleton can be erected on side spans and approaches and floated across the rivers. In cold climates the steel skeleton can be erected on the ice cover and lifted onto the pillars.

In coastal regions the network arch can be lifted in place by big floating cranes. The steel skeleton of spans over 250 m can be moved into place in one piece. For long bridges with many spans network arches can be made on shore from high strength concrete and lifted in place by big floating cranes. [i] Page 40. Because the network arch is so light, the spans of network arches should be longer than the spans of conventional designs. Savings in the substructure contribute to the considerable savings.

It is mainly up to the bridge authorities to promote the optimal network arch. If they do not accept it, nobody can build it. General conservatism might be the main reason if this promising type of bridge is not built. That is a shame because it could help reduce poverty.

1 INTRODUCTION

The advantages of the network arch can be explained by comparing them to earlier types of bridges. The author will try to explain why the optimal network arch is so light. It will be compared to the concrete arch bridge in fig. 1 built in Thailand in 1942[ii]. The hangers were steel rods that cannot take compression. For the loads and materials used between the two World Wars, this was an efficient structure.

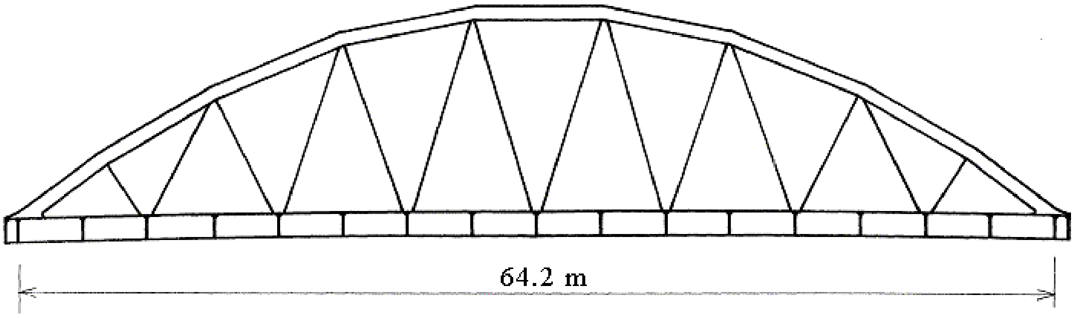

Fig. 1.The Manam Pasak Bridge in Thailand

With today's bigger loads and stronger materials many hangers might relax due to one sided loads. This would lead to bigger bending moments in the chords. See fig. 2.

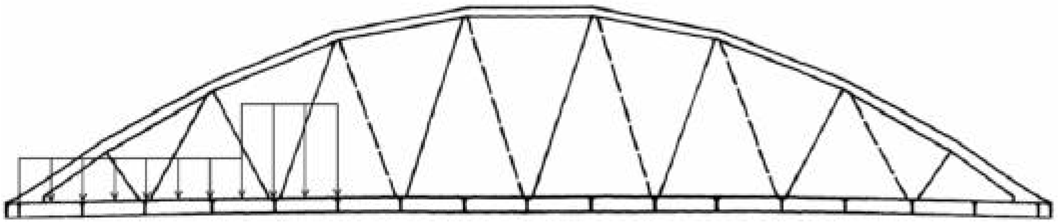

Fig. 2. The bridge in fig. 1 with modern materials and loads

The hanger's tendency to relax might be counteracted by increasing the distance between the nodal points. This leads to increased bending moments in the lower chord and increased buckling strength in the arch. See fig. 3. Here the arch has continuous curvature. This normally looks good, but it causes bigger bending moments in the arch. Between the nodes the arch has a tendency to move upwards. In the lower chord there is a similar tendency to move downwards. Thus it is a good idea to put in one or two extra sets of hangers as shown in fig. 4.

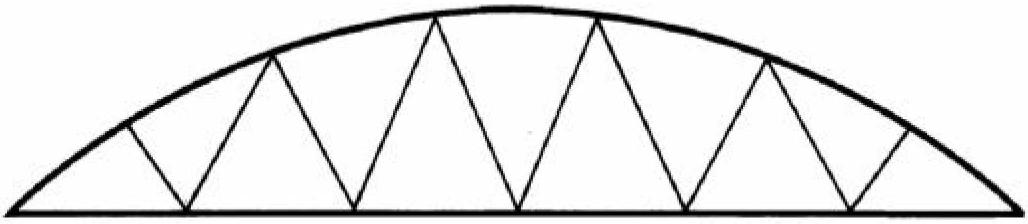

Fig. 3. Increased distance between nodal points gives decreased tendency for relaxation

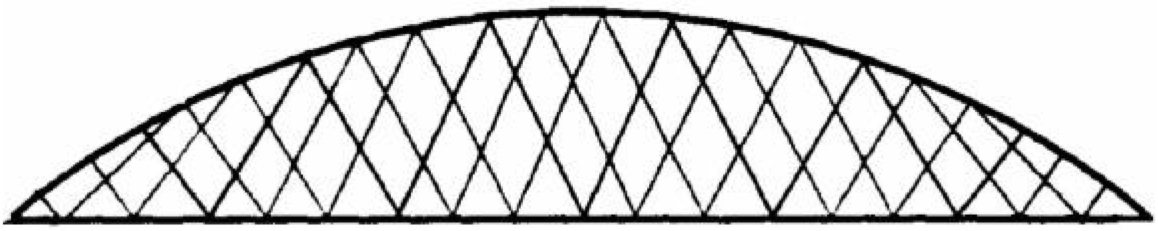

Fig. 4. Tied arch with three sets of hangers

Two or three sets of hangers give reduced buckling lengths in the arch and less bending in the chords. Furthermore it will be easier to decrease the hanger's tendency to relax. In the Bolstadstraumen Bridge[iii] built in 1964 the hangers are placed evenly distributed along the arch. The slope of the hangers is chosen to obtain a suitable resistance against their relaxation and nearly equal maximum force in all hangers. See fig. 5

It is reasonable to define the slenderness of an arch bridge as the span of the bridge divided by the combined sum of the depth of the chords. The slenderness of the Bolstadstraumen Bridge is 91. It has been the world's most slender arch bridge for 41 years. If the author's design of the Brandanger Bridge in fig. 11 is built, it will be three times as slender.

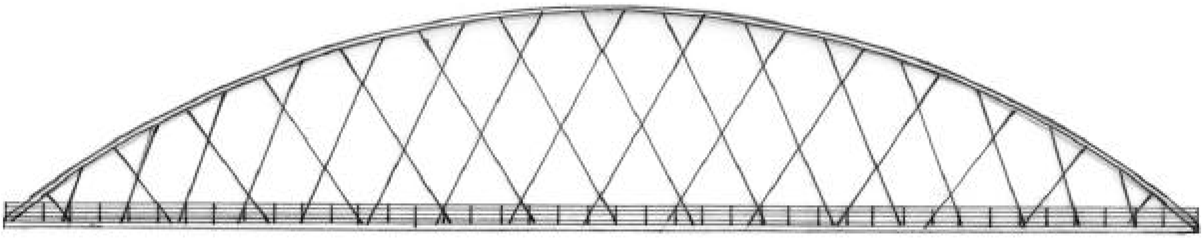

Fig. 5. Bolstadstraumen Bridge built in western Norway in 1964. Rise of arch 0.18 times span.

The bridges in figs. 1 to 5 can be seen as simply supported beams. The hangers form a very light web. Most of the shear force is taken by the vertical component of the force in the arch. Some of the variation in the shear force is taken by the variation in the hanger force. The hangers distribute the load between the chords in such a way that there is very little bending as long as all but a few hangers are in tension.

The tension and compression zones of simply supported beams correspond to the chords of the network arches. The axial forces in the chords are inversely proportional to the rise of the arch. Thus a high ratio between the rise of the arch and the span leads to smaller forces in the chords. This saves materials. For aesthetic reasons the author would be reluctant to use a high rise in the arch. In road bridges the author would be reluctant to let the rise of the arch exceed 15% of the span. The rise of the bridge in fig. 5 was chosen because the rise of a competing bridge was 0.205 times the span.

Even with a moderate rise in the arch, the network arch is an efficient structure for these 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 sideways support from the hangers, and so there is little tendency for buckling in the plane of the arch. Every part of the structure makes good use of high strength steels.

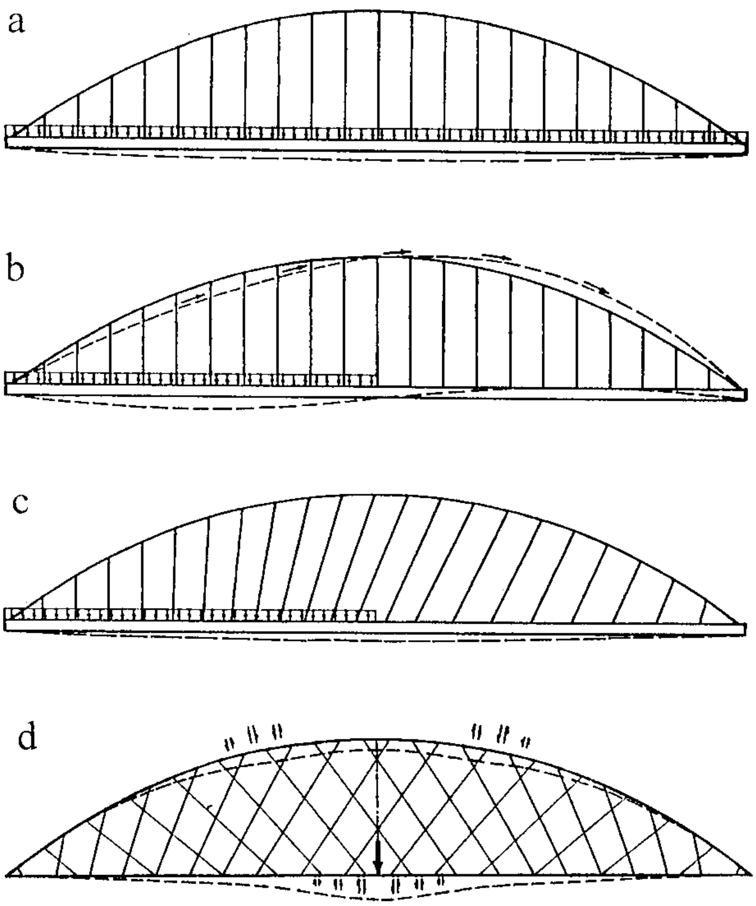

Fig. 6 illustrates advantages of the network arch

A usual arch bridge with vertical hangers is shown in fig 6a. It works best when there is a constant load on the whole bridge. Then the loads are transferred to the supports by axial forces. A load on part of the bridge gives much bending in the chords. Loads and deformations are shown in fig. 3b. To take such loads, the arch or the tie must have high bending capacity.

The loads can be reduced by giving the hangers a slope like in fig. 6c. For every skew load there is an optimal slope of the hangers. With an increasing ratio of skew load to evenly distributed load the hanger's angle with the horizontal must be reduced. This speaks for making an arch bridge with two sets of hangers as shown in fig. 6.d.

When there is a live load on one side of the bridge, the biggest tension is in the hangers that are sloping away from the load. An evenly distributed load on the span can be seen as a combination of two skew loads that leads to small bending moments. The network arch functions so well because the hangers distribute the loads in such a way that they give predominantly axial forces in the chords.

Sometimes it is best to see the network arches in fig. 6d as many trusses on top of one another. They all have the same chords. The load P must be distributed in such a way that the chords have the same deflection. The arrows indicate the shear force in the chords. Local deflection is indicated by dotted lines.

The author has a problem when advocating the optimal network arch. Such a structure has not been built in the last 40 years. He can only point to two old network arches, to calculations and to possibilities and hope that you will take his advice.

It should be mentioned that the two Norwegian optimal network arches are still in very good shape. The network arch in fig. 5 needed 44 tons of structural steel and 7 tons of prestressing steel. The competing arch bridge with vertical hangers needed 125 tons of steel. A concrete slab spanning between the planes of the arches was the same for both bridges. The savings in steel are typical for network arches. In this contribution ton or t means metric tons.

2 STEEL WEIGHT IN NETWORK ARCHES

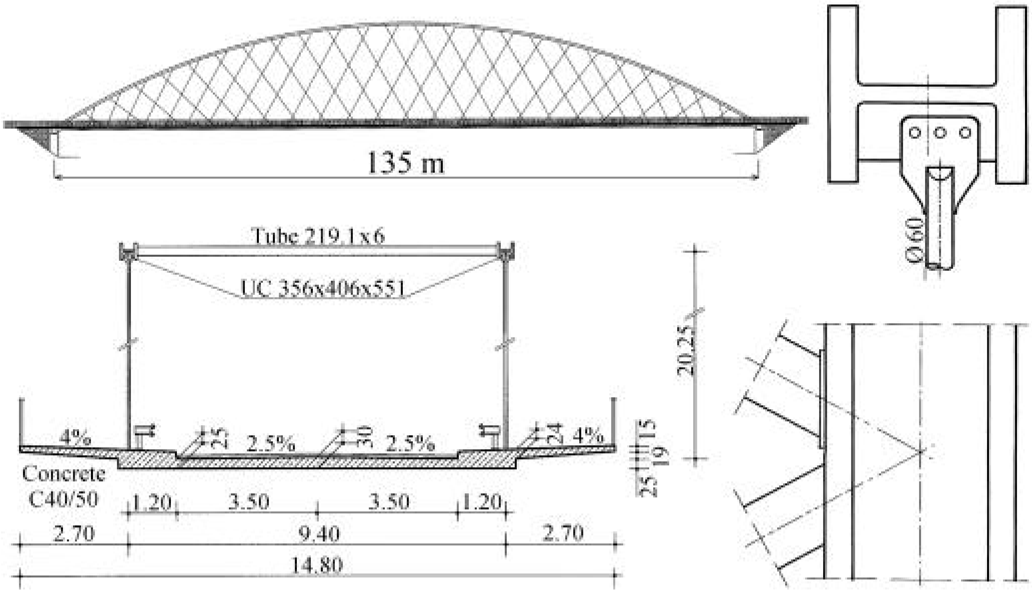

Fig. 6. Network arch designed according to EU codes. The calculations are at http://fag.grm.hia.no/fagstoff/pert/

Teich and Wendelin designed the bridge in fig. 6 in 2001[iv]. Teich was the best engineering graduate in TU-Dresden that year. He is present at this conference to tell us about fatigue in hangers of network arches. In fig. 7 the steel weights of German arch bridges with vertical hangers are compared to the steel weight of the bridge in fig. 6. The year that the bridges were built is indicated. Bridges marked N have no windbracing. In bridges marked S the arches slope towards each other.

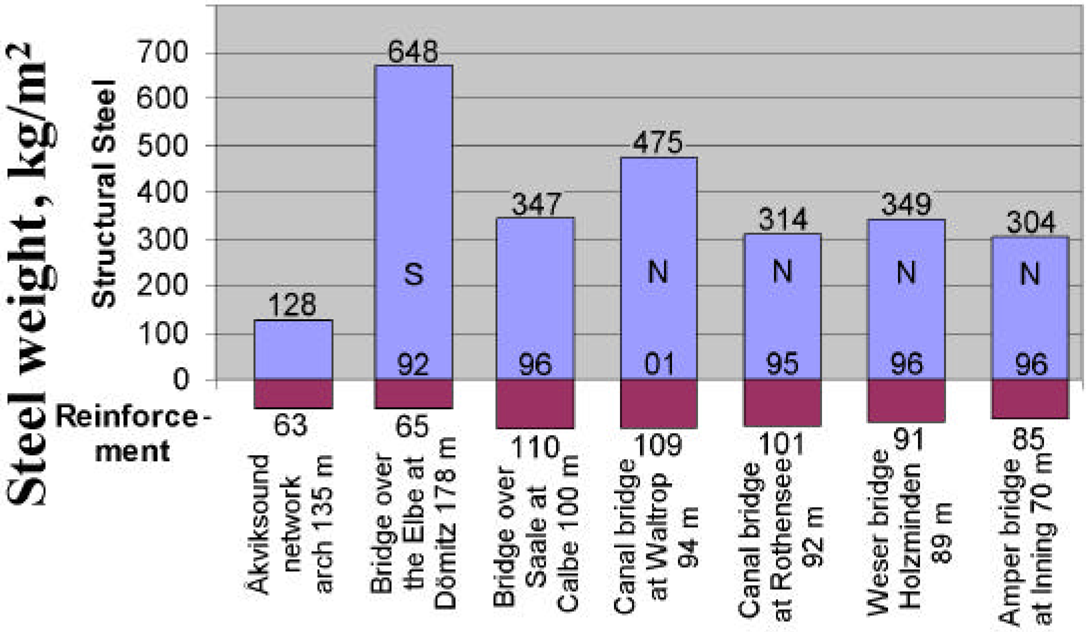

Fig. 7. Steel weight per square metre of bridge area for various arch bridges.

It is surprising that the optimal network arch tends to use less reinforcement in the tie than the bridges that have steel beams under the concrete slab. Part of the reason for this is the high amount of minimum reinforcement that is needed in the slabs that are lying on top of the elongating longitudinal steel beams. In optimal network arches the moderate longitudinal prestress in the serviceability limit state reduces the need for minimum reinforcement. This longitudinal prestress is part of the reason why the concrete in the two Norwegian network arches is in such good shape after more than 40 years.

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

Fig. 8 compares the optimal network arch to arch bridges with vertical hangers

5 AN ECONOMIC APPLICATION OF THE OPTIMAL NETWORK ARCH

In his work with network arches the author has presented influence lines and quantities to make it easy for fellow engineers to check his claims concerning saving of materials[i,iii,v]. The author has been reluctant to specify savings in dollars or sterling because such savings are much more difficult to defend. Network arches have little welding and simple details that repeat themselves many times. Thus the price per ton of the steel in optimal network arches will not be high. See also fig. 8.

The reduction in cost resulting from the use of network arch bridges is of great interest. Therefore an arch bridge with vertical hangers spanning 100 m built over the River Saale near Calbe in Germany[vi] is compared to a network arch with a span of 150 m.

At similar sites network arches should normally have longer spans than other bridge types. This is because the steel weight of the network arch is smaller and increases more slowly with increasing spans. The data for the network arch are based on the network arch in fig. 6[iv].

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

The network arch with a span of 150 m will need about the same supports as the 100 m arch bridge with vertical hangers. EU loads and codes are used for both spans. Some factors that influence the cost of the two spans are presented.

Permanent load per span:	Calbe	Network arch	
Structural steel	530 t	255.1 (150/135)^2=	315 t
Railings 200kg/m	20 t		30 t
Reinforcement	151 t	126.2 (150/135) =	140 t
Concrete	1463 t	1358 (150/135) =	1509 t
Asphalt,etc. 80mm	136 t		197 t
	S 2300 t		S 2191 t

Live load on a support: Calbe, area 1390 m^2: ((9.0-2.5)·3·100+ 1390·2.5)0.981/10=532 t
Network arch, area 2205 m^2: ((9.0-2.5)·3·100+ 2205·2.5)0.981/10=828 t

The load on a support due to concentrated live load is about the same for both bridges.

The live load on each support is added to the permanent load on the support after it has been multiplied by the relevant partial safety factors $?_Q/?_G$:

Calbe: 2300+532(1.5/1.35)=2891 t
Network arch: 2191+828(1.5/1.35)=3111 t

Area exposed to wind:

	Arches and tie	Hangers	Railings	Traffic	
Calbe:	(0.9·2+2)100	0.12·207[m]	1·100	2·100	S 701 m²
Network arch:	(0.424·2+0.6)150	0.06·1528[m]	1·150	2·150	S 759 m²

The vertical load on the support is about 7 % smaller for the Calbe Bridge.
The area exposed to wind is approximately 8% smaller for the Calbe Bridge.
The useful area of the bridge is approximately 6 % smaller for the Calbe Bridge.

Since the span of the Calbe Bridge is 33 % smaller, the saving in the pillars when using the network arch is likely to be between 25 % and 32%.

Comparison of the superstructure of the Calbe Bridge with a span of 100 m and a useful area of 1390 m² to a network arch with a span of 150 m and a useful area of 2205 m²:

	Calbe	Network arch	Reduction per m^2 of useful bridge area
Structural steel	530 t	315 t	63 %
Reinforcement bars	151 t	140 t	42 %
Concrete	1463 t	1509 t	35 %
Steel skeleton to erect:	530 t	~400 t	24 %

All comparisons will be lopsided. These additional facts should be taken into consideration: The network arch makes better use of high strength steels. The yield strength of the steel in the Calbe Bridge is 345 MPa compared with 430 MPa in the network arch.

The rise of the arch is 17 % of the span in the Calbe Bridge and 15 % of the span in the network arch. In the network more than half of the reinforcement is straight bars perpendicular to the planes of the arches. It can be shipped directly from the steelworks to the site. More than 90 % of the reinforcement is straight bars.

In the network arch the arch and the hangers protrude from the bridge area making the bridge area less useful. This is partly compensated for by widening the network arches up to 1.2 m at the ends of the span. This widening is not included in the useful bridge area mentioned above.

The author thinks that using the network arch can save between 40 % and 50 % of the cost of the superstructure. The author also thinks that using the network arch instead of the arch with vertical hangers can save between 35 % and 45 % of the cost per m². Many good civil engineers will not believe that these savings are possible. The author hopes that a few of them will try network arches at suitable sites.

On the author’s homepage there are two publications on how to make a preliminary design of a network arch. The purpose of the publications is to arrive at the preliminary dimensions that can be put into a general frame program. The publications would also be a good help to anyone who wants to find the amount of materials needed in a network arch. The spans are 93, 120, 135 and 160 m. If anybody makes a careful comparison of the cost of an optimal network arch bridge spanning more than 100 m with other types of bridges, the author would like to know the results.

4 ERECTION OF NETWORK ARCHES

The tie of the two Norwegian network arches was cast on timber structures resting on piles in the river bed. 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.

Fig. 8 shows the first stage in the erection of an optimal network arch spanning 100 m. It has a 45° angle with the channel it is going to cross. To keep the thickness of the slab down, three arches are used.

The structural steel and the temporary lower chord are erected on the side-spans. Afterwards no adjustment of the hangers is necessary. The steel skeleton is moved to its final position by means of a pontoon.

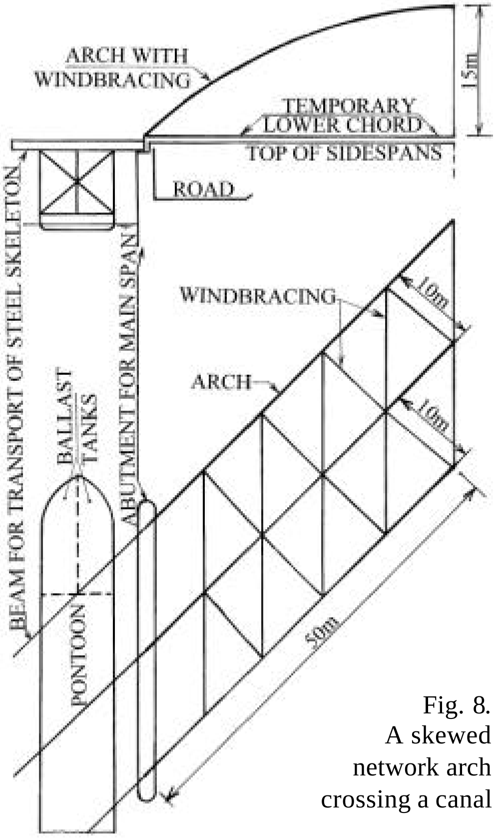

Fig. 8. A skewed network arch crossing a canal

First one end of the steel skeleton is rolled onto the middle of the pontoon, while the other end rolls on the side spans. No strengthening of the side-spans is needed. Then the pontoon is pulled to the other side of the canal and the steel skeleton is rolled to its final position. Then the tie is cast. After the tie is cast, the temporary lower chord is removed.

5 USE OF BIG CRANES IN THE BUILDING OF NETWORK ARCHES

Fig 9. Cranes for lifting the Shinhamadera Bridge, 1991

Fig. 9 shows the lifting of a 254 m network arch[vii]. The typical Japanese network arches have steel bridge decks. The hangers are placed equidistantly along the tie at the ends of transverse beams. The hangers have a constant slope.

The Japanese network arches use much more steel than the author's optimal network arches. Their methods of erection use to demand deep chords.

The cranes in fig. 9 can lift 3500 tons each. The span was lifted onto a pontoon and floated to the site where it was lowered on the pillars at tide.

The lightness of the network arch makes it well suited for being lifted in place by big floating cranes. Two examples of floating cranes deserve to be mentioned: One crane can lift 8200 tons up to 80 m above sea level. Another crane can lift 1650 t up to 110 m above sea level. In costal regions such a crane can lift the steel skeletons of network arches spanning over 250 m. Two big cranes working together can lift almost any span.

Depending on local conditions, and the cranes available, the cranes could lift finished spans with steel arches or spans made exclusively of high strength concrete.

Normally the steel skeleton can only be lifted at both ends, but it can also be lifted as shown in fig. 9. The cables between the steel skeleton and the crane are the prestressing cables that later will be used in the lower chord. The steel skeleton weighs less than 300 tons.

Fig. 10. Lifting of the steel skeleton of the bridge in fig. 6

6 THE BRANDANGERSOUND BRIDGE

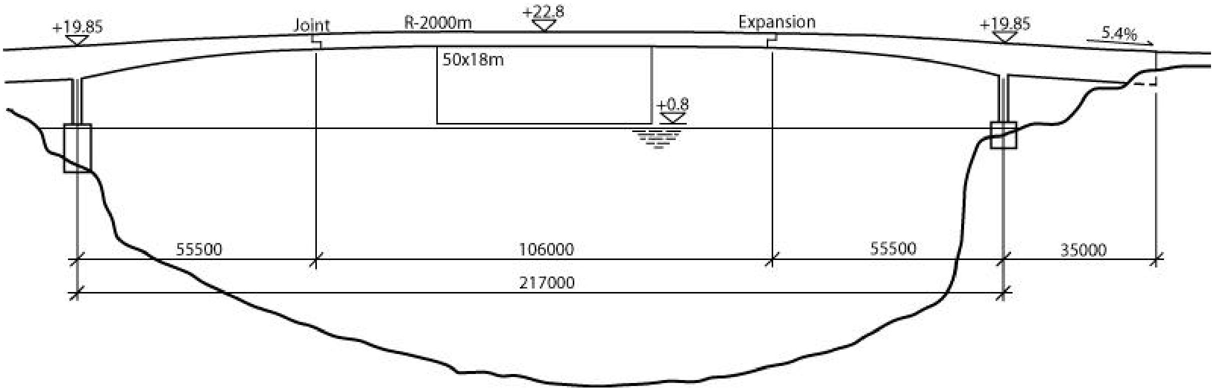

Fig. 11: Suggested steel box bridge for the Brandangersound in western Norway.

The bridge in fig. 12 seems to need 500 tons less steel than the bridge in fig. 11. The eastern approach to the main span is rock fill with the normal width of a two lane road. The tie of the main span can be cast on the asphalt of the approach. When the main span is finished, one end of it can be lifted across the sound by the crane in fig. 10. That crane has a capacity to lift 600 tons to 60 m over the water. The other end rolls on the approach.

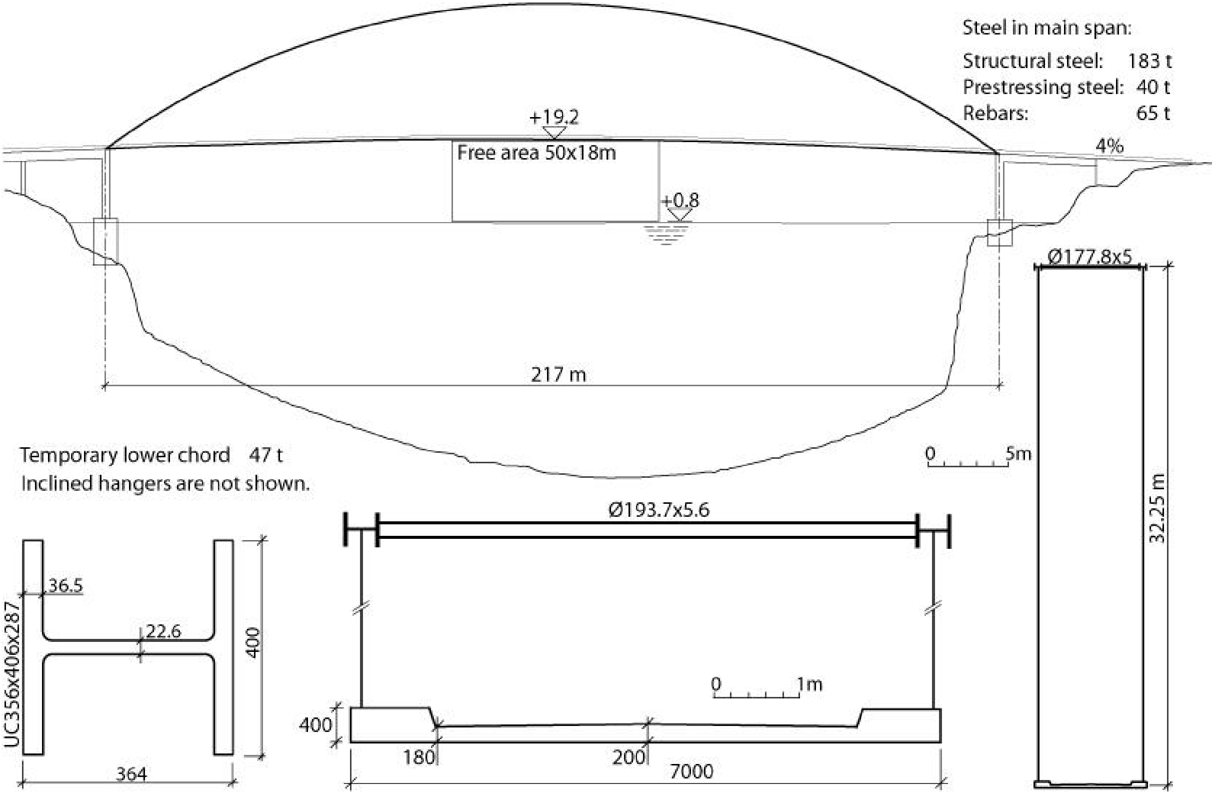

Fig. 12 shows a suggested network arch for the Brandanger Sound

If the approach east of the bridge had not been rock fill with a suitable curvature, it might have been costly to strengthen the side spans till they could carry the moving of the east end of the main span. Then a steel skeleton which would weigh around 250 tons could be lifted in place. The steel skeleton can carry the concrete tie while it is cast. It might be difficult to lift the steel skeleton in place by the crane in fig. 9. If there is not enough room between and the steel skeleton the lifting might introduce too much bending in chords.

If the steel skeleton is assembled on the side spans, it can easily be pulled across the sound before the tie is cast. If the main span or the steel skeleton is built far from the bridge site, two cranes could bring it in place, but it would be best to finish the main span on the rock fill of the eastern approach. The calculations for the Brandangersound Bridge are not quite finished yet. Any deviating results will be presented in Barcelona later this year.

7 WHY ARE OPTIMAL NETWORK ARCHES NOT BUILT?

An obvious explanation might be that optimal network arches are not economic. The author is not willing to accept this explanation and will try to come up with other reasons. The two Norwegian network arches, for instance the one in fig. 5, were built because they were less costly than competing alternatives. Designs like the one in fig. 6 are more cost efficient. Furthermore the optimal network arch has low maintenance cost.

Designers might be reluctant to build optimal network arches because they are afraid that they might collapse if lorries collide with the hangers. In the network arch the hangers that are near each other at the lane are well spaced at the arch. When the hangers break, it is assumed that the span does not have maximum load. Thus a lot of hangers have to be broken before the arch collapses.

The tension in the prestressing cables will prevent a rupture in the lower chord till a lot of hangers are broken. Near the end of the arch the hangers are not so well spaced, but here the arches are stronger. Collision between lorries and superstructure is a problem whenever structural members are above the lane. It is not much more serious in optimal network arches.

When network arches are built, the steel and concrete contractor will have to work together in new ways. In most cases the steel skeleton has to be erected first. Then the steel skeleton is moved into place. Then the formwork is finished and the casting of the tie is done. Finally the formwork and the temporary lower chord are removed, probably by the steel contractor. This calls for a close cooperation and that is an extra difficulty.

Steel firms have little interest in bridges that need so little steel. The concrete firms would like to see more concrete. The introduction of the optimal network arch would give extra work for bridge design firms, and there is a general shortage of engineers that can be trusted with designing the first network arch. Everybody has lots of intriguing engineering problems that they would rather study.

To some civil engineers the author’s claims may seem exaggerated, but it would be stupid to exaggerate when the bare facts seem like an exaggeration. The introduction of the optimal network arch would give extra work for the bridge authorities, but the author hopes that they will find the time and the courage to promote network arches. General conservatism might be the main reason if this promising type of bridge is not built.

8 CONCLUSION

In network arches bending moments are small. The hangers give the arch good lateral support. All members in an optimal network arch efficiently carry forces that cannot be avoided in any simply supported beam. Therefore it is a most efficient structure.

Combined with suitable methods of erection the optimal network arch must be an economical solution. The most promising methods of erection use a temporary lower chord which combined with the structural steel has enough strength and stiffness to carry the casting of the concrete tie.

In cold climates the network arch can be erected on ice and be lifted onto the pillar. In coastal regions big floating cranes can be used for erecting network arches. Spans of 250 m can be lifted in one piece. Depending on the cranes available and the number of spans, steel skeletons, network arches with steel arches or network arches made of concrete may be used.

The tie of the optimal network arch is a simple concrete slab. This gives the shortest possible ramps when a flow of traffic must be lifted to pass navigable waters. The optimal network arch is likely to remain the world's most slender arch bridge.

The building of optimal network arches can bring great savings. Considering the great poverty in the world, it would be morally wrong not to use them at suitable sites. It is up to you, ladies and gentlemen, to counteract the general conservatism that prevents the use of this very promising structure.

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