

Adjustment of hangers in network arches

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Fig. 1 Network arch in Rhode Island, USA. To be completed in 2007.

Introduction

The origin of this lecture lies back in 1963. Then the author presented the design of the bridge at Steinkjer, see fig. 2 and 3, at a lecture for colleagues in The Technical University of Norway, Trondheim. Professor Ray Clough, who is considered to be the inventor of the element method, happened to be present. Professor Clough expressed doubt that the hangers could be adjusted in such a way that the arch had very small bending moments due to dead loads. The author had to answer that he thought it possible, but secretly he was worried about having to solve the problem.

How the problem was solved was the theme of a lecture that the author was obliged to give in 1964 to obtain his present title of dr. ing. This publication is based on that lecture, which contributes to making the publication more longwinded, even though some parts have been updated and shortened.

Patricia Steere of the Maguire Group, Inc. has asked the author for an English version of the lecture. She is responsible for the design of a network arch in Providence, Rhode Island, USA. Fig. 1. [Tveit 02]. The author is very pleased that somebody has asked for the information given in a lecture 38 years ago. Increased knowledge and experience have resulted in some alterations in the old manuscript. Over one hundred pages on network arches can be found at, <http://pchome.grm.hia.no/~pert/> Those pages will be updated at irregular intervals.



Fig. 2. Bridge at Steinkjer, Norway, opened in June 1963.

In the calculations we usually assume that the structure has no stresses if it has no loads. If network arches shall live up to these assumptions, meticulous attention to the shape of the structure is necessary. In the two network arches built in Norway [Tveit 00] this meant careful adjustment of the length of the hangers. Careful measuring of the form of the elements of the arch prior to the erection of the steel was also important.

Sometimes it is clear that a deviation from the assumption of “no load; no stress” is not important. It might even be beneficial. It is for instance difficult to obtain the correct length of the shortest hangers in a network arch, but it is normally not too difficult to obtain a state of stress that is equally or more favourable.

The arch and the hangers, supplemented by a temporary lower chord, could be erected on the side-spans before this steel skeleton is moved to the final position of the span. If the arch has the correct shape and the hangers have no slack and very little tensile force, no further adjustment of the hangers is necessary. At Steinkjer, fig. 2 and 3, the deck of the bridge was cast on a timber structure resting on wooden piles driven into the riverbed. The deck was a convenient platform for erecting the arch and hangers.

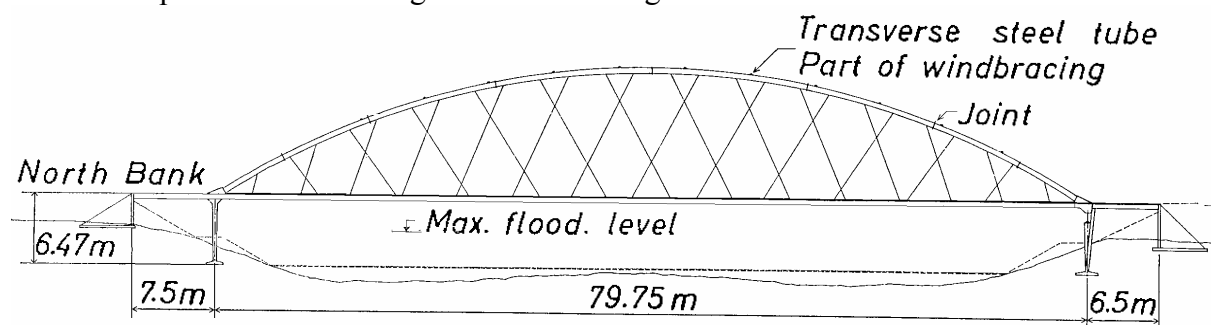


Fig. 3. Drawing of the network arch at Steinkjer.

General reasoning

Network arches will be calculated by means of big computer programs. The forces and deflections due to dead load are calculated in advance. That helps to make the adjustment of the shape of the network arch less difficult.

Fig. 4 shows the slender steel columns that supported the erection of the arch of the Steinkjer Bridge. Some of the hangers were not installed until the steel columns supporting the arch were removed. This erection could not give exactly the correct shape of the arch. Careful adjustment of the hangers was necessary. The lower end of the hangers in the Steinkjer Bridge is shown in fig. 5. After arch and hangers were erected, the hangers were tightened till they carried the concrete deck. Then the timber structure was removed.



Fig. 4. Erection of the arch of the Steinkjer Bridge.

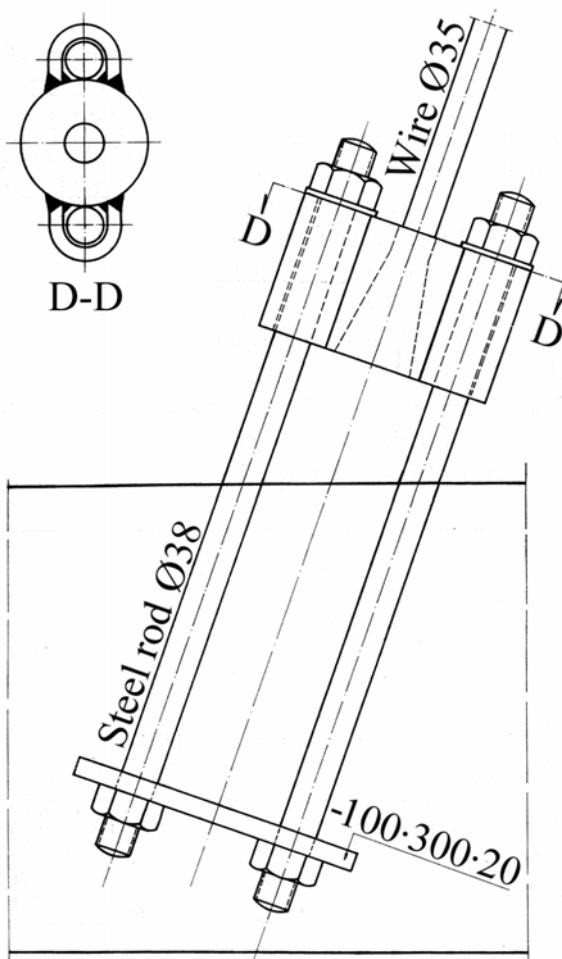


Fig. 5. The lower end of a hanger on the bridge at Steinkjer.

In the two Norwegian network arches the hangers were made of cables that consisted of 37 compact, galvanized round strands. In the Steinkjer Bridge the diameter of the hangers was 35 mm. In Bolstadstraumen Bridge in Western Norway the diameter of the hangers was 32 mm.

Two kinds of observations can be made when adjusting the shape of network arches. One is the measurement of forces in hangers. The other is the measurement of shape and deformations of the chords.

Many methods can be used to measure the tension in the hangers. Japanese engineers have found the tension in hangers from the frequency of the first mode of vibration of the hangers. The author has written to Japan to obtain a reference. The forces in the hangers can be measured by strain gauges. At Steinkjer and Bolstadstraumen the following method was used:

A transverse load of 2 kN was applied to the middle of the hanger or 4 to 4.5 metres from the lower end of the wire in the hangers. It was too complicated to push the transversal load further up. Then the deflection of the hanger was measured by sighting along the upper part of the hanger and measuring the deflection near the lower end of the hanger. See fig. 6.

In shorter hangers putting up a string line between the ends of the hanger and measuring the deflection due to a transverse load on the hanger can give a better measurement of the force. See fig. 6. The hanger is bent in the middle and at the ends. The measurements should be taken in the part of the hanger that seems straight. It is a good idea to avoid using very short hangers. If sufficient strength is provided at the ends of the arches, it seems best that the first hanger slopes away from the end of the arch like in the Steinkjer Bridge.

To obtain precise measurements by sighting along the hangers, two men should independently measure the deflection. From careful measurement under an overcast sky, the average deviation between the men's measured deflections was 1 mm. This corresponds to a standard deviation in an average measurement equal to 0.7 mm. The standard deviation of the average of two measurements was 0.5 mm. For the Bolstadstraumen Bridge the average deflection was about 100 mm.

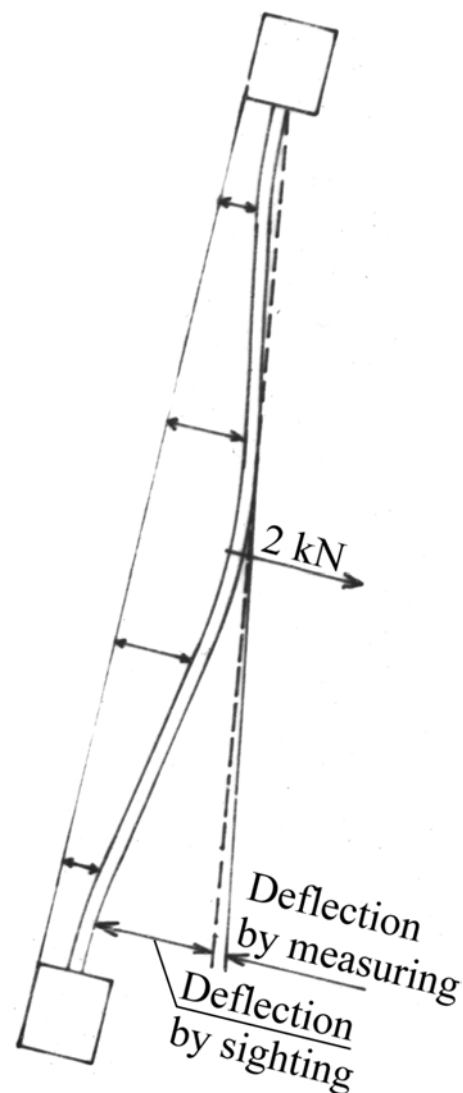


Fig. 6. Deflected hanger.

If we assume that the deviations have a Gaussian distribution, about two thirds of the measurements stray less than 0.5 mm from the exact value. It is a good approximation to assume that the deflection is proportional to the hanger force. Thus two thirds of the measurements of the hanger force have a deviation of less than 0.5 %.

Only 0.3 % of the measurements have a deviation bigger than 3 times the standard deviation. This means that only 0.3 % of the measurements give values that deviate more than 1.5 % from the real force in the hanger. In sunshine the faults in the measurements are about twice as big. When it is raining, the measurements are even less reliable.

The stiffness of the hanger will tend to make its sideways deflection smaller. This leads to a bigger measured force in the hanger. See fig. 6. The measured load in the hanger will be bigger than the real force because the transverse load increases the axial force in the hanger. This increase can be calculated by means of the computer program used for calculating the network arch. The increase is not big, and is about the same for adjoining hangers. This is good because it is mainly the difference in the force between nearly parallel hangers that we need to know.

Along the tie the cross-section and weight vary from the assumed value. It is hard to distinguish the effect of the uneven distribution from weight along the tie from the effect of built in stresses. However, this is not a cause for concern. If the correct shape of the span is achieved, the stresses in the structure due to the change in the weight along the tie will be small.

The self-weight of the hanger leads to a deflection in addition to the deflection due to the applied transverse load. This addition depends on the length and slope of every hanger. This makes the addition different for every hanger. For the Bolstadstraumen Bridge the deflection due to self-weight was up to 9.5 % for a hanger near the middle of the span. The computer program can calculate the transverse deflection due to self-weight and the likely sideways deflection due to transverse force of 2 kN.

In the two Norwegian network arches flanges joined the parts in the arches to each other. See fig. 2 and 3. The shape of the parts could be measured prior to erection. If the arches are not put on the side when the initial curvature of the parts of the arch are measured, there should be correction for the deflection due to self-weight.

The distance from a string between the tops of the flanges in the joints should be recorded before and during the erection and compared with the intended shape of the arch. Two parts of the arch are joined at each pair of flanges. The curvature of the arch at the flanges should be recorded prior to erection.

Since we know the shape of the arch between the flanges, it is practical only to measure the distance between arch and tie at each pair of flanges. This can be done for instance by suspending an iron band $0.3 \times 10 \text{ mm}^2$ with a load in the lower end of it from each flange. At a suitable level a bit of a levelling staff should be fastened to the iron band. The level of the bit of levelling staff can be found by using a levelling instrument. It is then easy to find the height of the pair of flanges by measuring their distance from the bit of the levelling staff.

The deformations in the tie are best measured by levelling. To increase the precision of the measurements, bits of metal or plastic should be glued to the concrete under the joints in the arch and possibly at the end of each hanger and other points of importance.

After the concrete tie has hardened, the level of all points in the tie should be measured. This is because the erection of the steel could give deformation in the tie. If a levelling telescope is used, the standard deviation in the measurement should be less than a millimetre. In the Bolstadstraumen Bridge two spectators on the bridge could give a deflection of about 1.5 mm.

Before the start of any serious tensioning of hangers, tension must be introduced in the prestressing cables. The maximum compression under the anchors of the prestressing cables is smaller if the prestressing is done in two steps. If the stressing of the longitudinal cables is done in one go, the anchor plates at the ends of the cables must be bigger.

The calculated tension in the hangers due to dead load gives an idea of how much the hangers will have to be tightened to carry the tie. See fig. 8 page 7. Furthermore the deflection due to the dead load gives an idea of how much the arch now must be pressed down in order to carry the loads on the bridge. These findings must be kept in mind when the arch is pulled towards the tie in small stages.

When the hangers have got some tension, continual checks must be made that the adjoining hangers have nearly the same deviation from the calculated value. If that is not the case, and the reason is not the uneven support from the timber structure under the bridge, the situation must be corrected. If the tension is too little, the hanger must be given extra tensioning provided that the arch at the top of the hanger is not too far down. When the tension is too big, the hanger must be skipped in a round or two of tensioning.

While the hangers are being tensioned, the downward movement of the abutments at the end of the bridge must also be controlled. If the abutments move downwards, it might be necessary to remove the timber structure near the end of the abutment in order to avoid big stresses in the tie. Good sense supported by calculations must decide how much tension there should be in the hangers when the timber structure under the bridge is removed.

The decision about when to remove the timber structure will be influenced by the need for upward camber of the tie. A straight tie will look as if it is sagging. A rise of the tie of 0.1 to 0.2 % of the span should be considered. After the timber structure has been removed, it is harder to adjust the length of the hangers.

In the early stages of tensioning it is important to tighten the hangers to give the arch the right shape without introducing much force in it. Towards the end of the process the forces in the hangers become more and more important.

Execution

Since 1962 there has been a tremendous development in computers and programs for calculating forces in network arches. Calculation of the forces in a network arch has become much easier. This should strongly influence the way in which the tensioning of hangers is done. Therefore the instructions from 1962 for adjusting hangers are outdated. The instructions presented here are shorter and maybe clearer than the instructions that the author presented about 40 years ago.

Today it is easier to see what changes should be made and to follow the development towards satisfactory shape and forces. Some data must be worked out before starting serious tensioning of the hangers. Fig. 8, see next page, indicates information that could have been presented for the Bolstadstraumen Bridge.

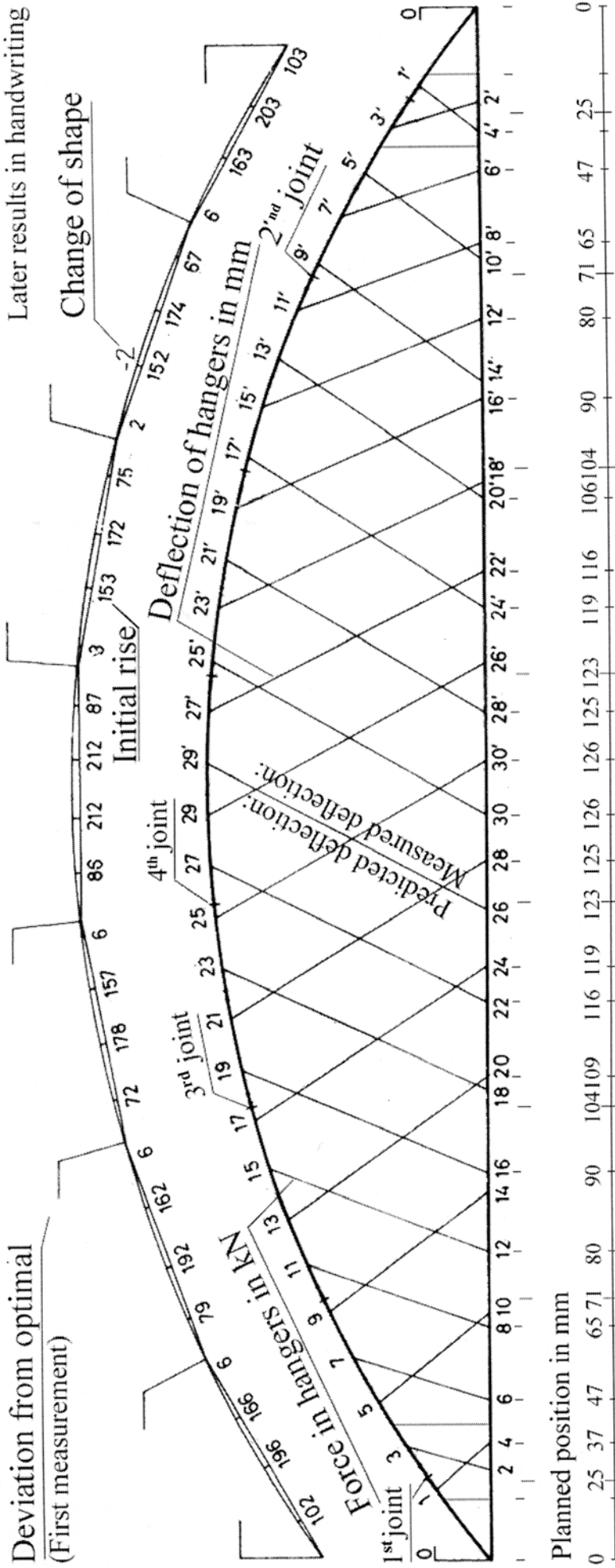
Most of the numbers in fig. 8 are illustrations, not the correct values. Initial, planned and calculated results are printed. Later results are in handwriting. Forces in hangers correspond to dead load prior to laying of asphalt. Deflections of the hangers are calculated for dead load.

The numbers under the top curved line give the measured deviations from straight lines between the tops of the flanges. Numbers at the flanges over the top curved line could give the deviation from the calculated position of the flanges. The numbers below the nodal points in the tie indicate a desirable calculated position of the nodal points. For each hanger predicted and measured deflections should be given. See fig.8.

The numbers in the first line below the tie in fig. 8 correspond to a camber of 0.15 % of the span. Below is the initial position of the tie. Then comes a planned shortening of the hangers by 60° turns of the two nuts at the ends of each hanger. See fig. 5. Then comes obtained position of the tie in mm. The two bottom lines in fig. 8 show how lagging joints in the arch of the Bolstadstraumen Bridge can be pulled towards the tie without introducing too much bending in the arch.

After these preparations the serious tightening of the hanger can start. It is important to have a good crew for the job and to avoid too much disturbance of the crew. After the supports for the arch have been removed, the hangers are gradually shortened to pull the arch towards the tie. The arch should be pulled down in small stages. It is not necessary to control and measure everything in every round of measurements.

Initial and planned results in print
 Later results in handwriting



Initial position in mm
 Planned change in 60° turns

Obtained position in mm

Shortening of hangers to move joints down. Change in 60° turns

2 nd joint: 3	0	6	63	3	5	0	1	0	5	0	5	0	33	60	6
3 rd joint: 1	0	5	0	0	5	0	3	0	5	0	5	0	2		
4 th joint: 3	2	50	6	0	4	3	0	5	0	5	0	2			

Fig. 8. Plan for adjustment in Bolstadstraumen Bridge.

Bigger stages would save time, but it is important to be sure the joints in the arch move gradually towards the tie. Between each stage the shape of the network arch and the tension in the hangers should be measured. Then new instructions on the tensioning of the hangers should be issued.

In long bridges with slender hangers extra care must be taken when tensioning the hangers. If a hanger does have too little tension, it might be because it has become too short. This might have given the arch too big a radius of curvature near the hanger. In this case the hanger could be tensioned till the network arch collapses.

The change in the length of the shortest hangers must not be allowed to introduce too big bending moments into the wind portal. To control this, the shape at the ends of the arch and tie must be recorded before the tightening of the hangers starts. This can be done for instance by measuring the distance between the arch and the tie 3 and 7 metres from the end of the arch. Later these distances must be kept in the region where calculations say that they ought to be.

The hangers influence each other so they have to be adjusted in several rounds. How big extra stresses should be accepted due to imperfect adjustment of hangers must be considered during the design. It must be influenced by the erection and fabrication tolerances especially if the buckling is calculated in the deflected state. It is fairly common that steel structures usually have extra stresses due to imperfect fabrication and erection. There is no reason why the network arch should be an exception.

In bridges with three sets of hangers the two sets of inclined hangers should be adjusted first. The nearly vertical set of hangers should be adjusted afterwards. This is however not the place to enlarge on this subject.

Conclusion

At the end of this publication the author would like to say that the unavoidable stresses due to adjustment of hangers in network arches are very small. Extra stresses due to imperfect fabrications are not likely to be bigger than in other steel structures.

References:

Tveit, P. [00] "The Network Arch" <http://pchome.grm.hia.no/~pert/> This internet edition will be updated at irregular intervals.

Tveit, P. [02]. "Optimal Design of Network Arches" IABSE symposium Melbourne 2002. ISBN 3-85748-107-2. P.136-138 and 11 pages on a CD-rom.