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Våla bridge - Timber network arch footbridge in Ringebu, Norway

Anna Weronika Ostrycharczyk[1], Arne Værnes

Abstract

This paper is about the Våla network arch timber footbridge, located in Ringebu, Norway. The bridge has one span of 52.5 m, and a 3.0 m wide footpath. The arches are made of glulaminated timber, the deck is made of prestressed concrete and hangers and wind truss are made of steel. In the first part of the article a simplified procedure for finding 'semi-optimal' network pattern is presented. It includes defining geometrical features such as: the arch rise, the number of hangers and the type of network pattern. There were 30 network outlines studied in the pre-design phase before the final pattern was chosen. In further part of the article, selected aspects of bridge design, such as material type for main elements and connectors as well as assumptions for numerical model are provided. Finally, description of the main tasks from the execution stage are presented. The article aims to show how to choose a network pattern in a simplified way, and that a network arch bridge can be a successful alternative to more traditional types for medium span timber footbridges.

1 Introduction

The concept of network arch bridge has been introduced in 1966 by Norwegian engineer Per Tveit [1]. Since then, network bridges were built all around the world, especially in Japan, USA and Europe, with emphasis on Germany and Norway. Traditionally, those bridges were made of steel or steel and concrete. In 2016 the first timber network arch bridge (Steien bridge) was built in Alvdal, Norway [2-3]. Since then, in Norway, timber become more often considered a serious candidate for building material for arches. As a result, network bridges with timber arches, like Hellefossbrua (opened in 2019), Prestmyra (opened in 2018) and presented in this paper – Våla footbridge (opened in 2020) has been build.

2 Choice of network pattern

The first part of the paper focuses on the hangers and network pattern, i.e., elements which influence structural performance of the bridge in a critical way. The main idea behind a network pattern is that forces which are acting directly on the deck, are transferred to the arch, just like in a classical arch-bridge with vertical hangers. However, in the network bridges, the 'mobilized' part of the arch is bigger than in the classical ones. Therefore, by using inclined hangers (network outline), the forces in the structure, mainly in hangers and the arch, are more uniformly distributed. This leads to smaller values of extreme forces and, as a result, to the smaller cross-sections of the structural elements.

There were three steps in the procedure of choosing a network pattern for Våla bridge. First, a set of 2D outlines of patterns was created, based on recommendations from the literature. In second step, visual grading was used to limit studied patterns. Finally, forces in hangers, from self-weight of simplified 3D numerical model, were used for pattern comparison.

In the engineering practice there are three most used network pattern types: pattern with constant inclination of hangers (CIH), pattern with constant change of hangers' inclination (CCI) and radial patter (RAD). Information about the patterns can be found, among others, in [4 -5]. In the pre-design phase of Våla-project only the two network pattern types, CCI and RAD, were considered since those patterns are more effective than CIH [6]. The principle of the CCI and RAD patterns outlines is shown in Figure 1.

[1] Anna Weronika Ostrycharczyk, PhD, Structural Engineer, Norconsult AS, Norway, anna.weronika.ostrycharczyk@norconsult.com

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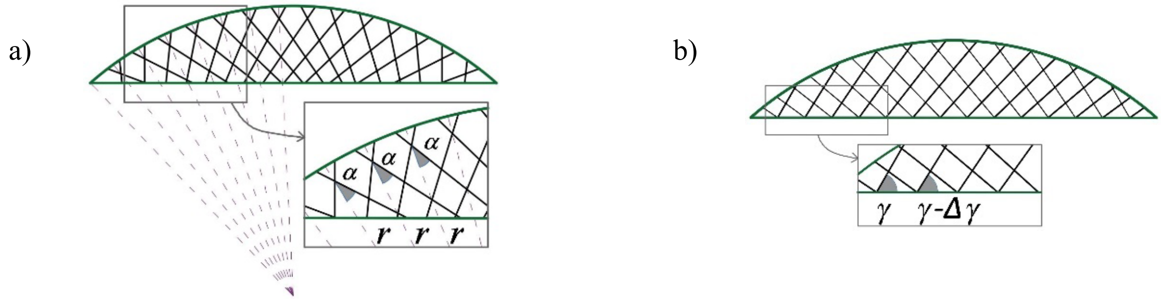

Figure 1 Principle for the outline of the network pattern; a) radial b) constant change of hangers' inclination

A total number of 30 different 2D network patterns was chosen for evaluation, before the final pattern was defined. Among those patterns, two arch rises were considered (8.0 m and 8.4 m), as well as three numbers of hangers (20, 22 and 24, which refers to all hangers in one arch). For the radial pattern, the angle α varied between 28 and 45 degrees. For pattern with constant change of hangers' inclination, starting angle γ varied between 70 and 80 degrees, while angle change $\Delta\gamma$ varied between 2,5 and 3,5 degrees. The parameters like arch rise and number of hangers were chosen based on the author's study [7, 8]. It was assumed that, in all considered patterns, hangers were evenly distributed along the arch. The outlines of the considered patterns are presented in Figure 2, while collection of patterns data and prescribed number of studied pattern is presented in Table 1.

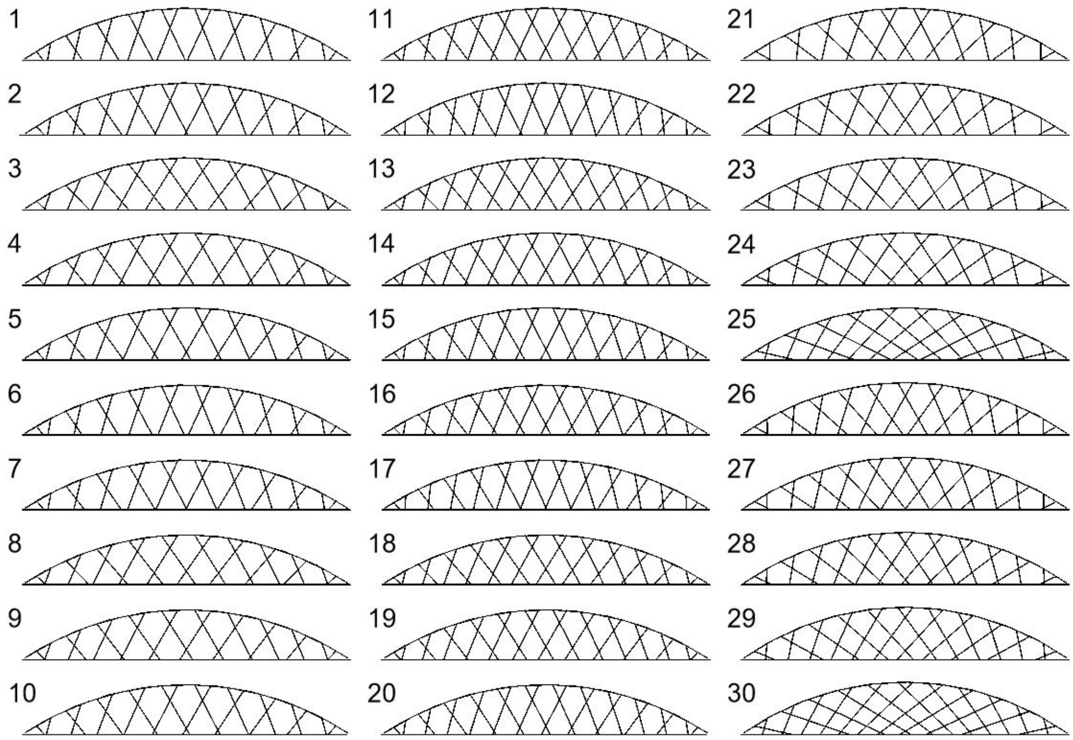

Figure 2 Patterns considered in the pre-design phase of Våla bridge

Table 1 Numbers and parameters of studied patterns

	Pattern type	**CCI**	**RAD**
		Pattern nr (1 to 20)	**Pattern nr (21 to 30)**
Arch rise	8.0 [m]	6 to 10; 16 to 20	-
	8.4 [m]	1 to 5; 11 to 15	21 to 30
Number of hangers	20 [-]	1 to 10	21 to 25
	22 [-]	-	26 to 30
	24 [-]	11 to 20	-

In the pre-designing phase, all 2D patterns were graded visually. The focus was on features listed below.

- The number of hanger's crossings.
  - It is desired, that most of the hangers cross at least twice.
- The location of hanger's crossings (especially on the deck level).
  - It was chosen to avoid two hangers 'landing' on the deck in the same point, or very close to each other, since it leads to the concentration of the stresses in the deck as well as the connectors cannot be unified. It should be pointed out, that patterns' outlines presented in Figure 2 refers to the centreline of the arch, deck and hangers, therefore the real hanger-deck connection point is located above the presented deck-line.
- The angle between the deck and the hanger.
  - Too steep inclination between the deck and the hanger leads to the high bending moment in the arch. It also leads to the big differences between minimum and maximum force in the hanger or making the hanger to slack.
- Aesthetics.
  - Although judgment after aesthetics is not fully objective, it was chosen to avoid patterns which creates two rows of 'rhombic' shapes with similar size along the bridge length.

Table 2 Results from visual grading of hangers

CIH				RAD	
Nr	Feature	Nr	Feature	Nr	Feature
1	X	11	●●	21	
2	X ●●	12	●●	22	●●
3		13	ae	23	<
4	X	14		24	●● <
5	●●	15	●● ae	25	<
6	X	16	ae	26	
7	X ●●	17	X	27	●●
8		18	ae	28	<
9	●● ae	19		29	<
10	●●	20	ae	30	<

X low number of hanger's crossings
●● location of hanger's crossings
< inclination between hanger and deck
ae aesthetics

Table 2 shows results from visual grading of all thirty patterns. Numbers 3, 8, 14, 19, 21 and 26 remained unmarked, thus were taken into further consideration. Those patters were used to create a simplified 3D numerical model, to study hangers' axial forces induced by self-weight. Both 2D patterns, and 3D models were created in semi-automatic way, by use of Python script in Dynamo in Revit, and Robot Structural Analysis Professional software [9-11].

In the numerical model the arch was built as a simple beam made of GL30h, with a cross-section of 500x600 mm. The arch was modelled as fixed to the deck at the ends. The deck was modelled as a shell element, made of concrete, with predefined thickens of 350 mm. Hangers, made of steel with diameter of 50 mm, were modelled as beam elements. All rotational degrees of freedom were released at both ends of hangers; thus, they could transfer only tension and compression. In final design, hangers were not exposed to compression. However, in the study-phase, presence of compression in hangers was a factor for determination which pattern's outline is most promising. The whole bridge was modelled like a simply supported beam.

Results from the influence of self-weight on force distribution in hangers, for six selected patterns, are presented in Table 3. The table shows maximum and minimum axial forces in hangers. Note, that a positive value refers to the tension and a negative value refers to the compression; it corresponds to the most common sign convention, and not to the sign convention form Robot Structural Analysis. It is clearly visible, that patterns 21 and 26 are more effective than the others, since all hangers in those two patterns are in tension. In addition, maximum force is smallest in those patterns.

Table 3: Axial forces in hangers induced by self-weight of the structure, for six selected full network patterns; results from pre-design phase

Pattern nr	3	8	14	19	21	26
Min [kN]	-39 *	-43	-53	-57	17	7
Max [kN]	173 **	184	169	177	154	155

* negative value = compression
** positive value = tension

Since the arches in Våla bridge were designed in glulam, and the deck was designed in concrete, it was natural to make the end part of the arch also in concrete. Such solution gives better force distribution in the arch-deck connection, due to uniform material and by avoiding mechanical steel connectors in this area. It is the architect and the designer who decide how long should this concrete part of the arch be. Technical limitations are mainly related to the necessary space for placing rebars and steel connector for glulam arch, casted at the end of the concrete arch. In Våla bridge, it was chosen to run the concrete arch from the deck up to the point of crossing with the first hanger in pattern. Simultaneously this first (and last) hanger was removed from the outline. In Figure 3, the removed hanger is presented as a dashed line. Removal of the first (and last) hanger, combined with the moment-resistant concrete end of the arch, influence positive on bending moments in the arch made of glulam. It leads to smaller values of bending moments.

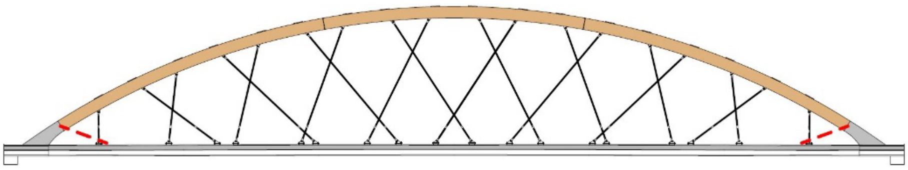

Figure 3 Outline of the network pattern with removed first and last hanger

Having the assumption of first (and last) hanger removed determined, numerical analyses for six considered patters were performed again. Results in form of the minimum and the maximum forces in the hangers, induced from the self-weight are presented in Table 4. Positive value refers to tension. Values in the table show, that with reduced number of hangers, there is only tensile force in all hangers of all studied patterns. However, it is also visible, that the difference between maximum and minimum force is the smallest in pattern 21 and 26. This suggest that those patterns are better than others.

Table 4: Axial forces in hangers induced by self-weight of the structure, for six selected network patterns with reduces number of hangers; results from pre-design phase.

Pattern nr	3	8	14	19	21	26
Min [kN]	28*	26	5	1	52	45
Max [kN]	119	120	114	117	93	85

* positive value = tension

Pattern 21 was chosen for further evaluation in the design phase. Pattern 21 is a radial pattern with angle α of 28 degrees between the arch radius and the hanger. The arch rise is 8.4 m. It was chosen over pattern 26 based on number of hangers: pattern 21 have 18 hangers in one arch (after removing fist and last hanger), and pattern 26 has 20 hangers (after the same reduction procedure).

In case of Våla bridge, difference of two hangers, between pattern 21 and 26, refers to cost of circa 80 thousand NOK (≈ 8 thousand EUR). Note that the cost of the whole bridge was circa 12 million NOK (≈ 1.2 million EUR).

3 Other designing aspects

In this part of the article, description of the structure and some selected aspects of the design of the bridge are presented.

The bridge is design for 100 years lifetime, based on requirements form Eurocodes and Norwegian handbook N400 'Design of bridges'[12] provided by The Norwegian Public Roads Administration. The bridge is 52.5 m long, and 5.9 m wide, while footpath is 3.0 m wide. The traffic load is defined as 5 kN/m^2 for pedestrian load, and 120 kN (40 kN + 80 kN) for a single, service vehicle. The deck is made of prestressed concrete with two tendons on each side. The thickness of the deck varies, between 350 mm in the middle and 650 mm on site, where the tendons are located. The arches are made of GL30h, with cross-section of 550x700 mm. The glulam is preserved by double vacuum-pressure impregnation with Cu-based salt and with creosote, which is still authorized for use in Norway. Creosote increases a self-weight of the wood. According to N400 addition for creosote is equal to 0,5 kN/m^3 or 0,8 kN/m^3 depends on which value is more unfavourable. In the calculations of Våla bru only one addition to weight, 0.8 kN/m^3, was used. The reason for that is small influence of the difference between the heigh and the low value of creosote addition (0.3 kN/m^3), which is less than 1% of weight of the whole bridge, thus negligible. The arches are protected mechanically in addition to chemical impregnation. They are covered with the zinc plates on the top, and with the wooden cladding on the outside, mounted in a way providing necessary ventilation. Due to chosen solution for timber protection, the serviceability class 2 was used in calculations. The arches are inclined towards each other with 6 degrees, which, in combination with wind-truss, provides stability in transverse direction. Although it is natural to make a wind bracing out of wood in wooden bridges, in Våla bridge it was chosen to use steel. Partially due to aesthetic, to balance out the steel hangers, and partially to avoid possible challenge of creosote dripping on the pedestrians.

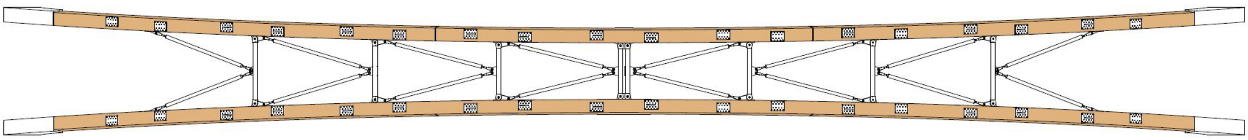

Figure 4 Outline of the wind truss in Våla footbridge.

Wind bracing, presented in Figure 4, is in K-shape and is designed of pipes made of standard carbon steel S355. There are two sizes of the pipes: the transversal ones are bigger, with diameter of 193,7x5mm, and the diagonal ones are smaller, 139,7x6 mm. Size difference is based on the aesthetics. To avoid axial forces in the wind bracing due to the difference in the E-module and temperature expansion in the wood and the steel, the top transversals of the K-shape are split in two independent pipes. Hangers, with diameter of 42 mm are made of carbon steel with minimum yield stress of 520 N/mm^2. Each hanger is divided into two parts, and those parts are connected with the turnbuckle which allows for prestressing the cables. In design process it was chosen to divide hangers on one level: ca. 1.2 m above the deck; see Figure 5. Such placing of division is favourite due to procedure for prestressing since all heavy equipment can be placed directly on the deck and additional lift is not needed. However, in case of some hangers, chosen division placing was located close to the crossing between two of them. It required additional check for space necessary to mount the turnbuckle. When deciding for hangers' division, additional aspect to consider was a minimum length of the lower part of the hanger, which was assumed 500 mm in the project. Finally, the shortest member of the cable was 892 mm long, spreading between the pin and the middle of the turnbuckle. Hangers are connected on the deck level to the steel connectors casted in concrete, and on the arch level to the 'T-plate'. Those 'T-plates' consists of two welded plates: one located on the top of the arch, and the other located in the hole in the arch; see Figure 6. Although usually a stainless steel is used for elements embedded in timber, material used for the discussed connector is a hot dip galvanized and powder coated carbon steel. Such choice was made to avoid contact between carbon steel and stainless steel: hanger vs connector. The connection is also considered replaceable, since it is screwed to the arch from the top and load combination for procedure of hanger replacement was taken into account in the calculations and design. Arch itself is divided in the three parts, see Figure 5. Here, all parts of timber-timber and timber-concrete connectors are made of stainless steel, with use of slotted-in plates and dowels.

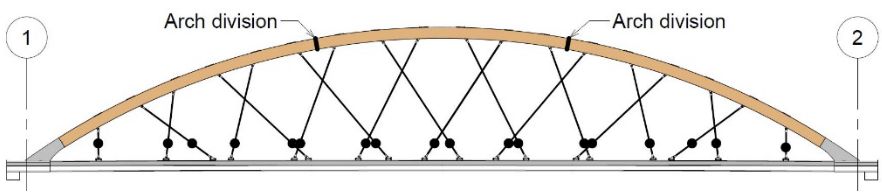

Figure 5 Division of hangers and arch

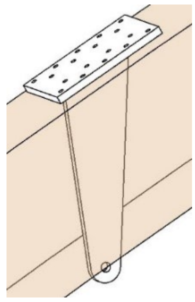

Figure 6 'T-plate' connector

Final numerical model of the bridge was created in Robot Structural Analysis Professional 2019. It was created in similar way to the model in pre-design phase. The deck was modelled as a shell, and the arch, hangers and wind-truss as beams. Considering boundary conditions, pinned support was modelled in one axis, and rolled support in the other axis. Releases of rotational degrees of freedom were placed at the end of hangers and each of element of wind bracing. Rigid links were used to connect the wind truss to the arch, to represent the real structure most accurate, since the beams representing the arch in the numerical model refers to the centreline of the arch. Arches were modelled with inclination toward each other. Connection between the concrete part of the arch and the deck was modelled as fully stiff. The stiffness of the connection at the end of the timber arch was reduced by 30 % in Rx, any by 10% in Ry and Rz directions, where Rx, Ry and Rz are rotational stiffness along the beam and transversally to the beam respectively. Connection between two parts of timber arch was modelled as fully stiff. The assumption for timber-timber connection was based on constant compression in the arch, and positive influence from wind bracing on bending moments, especially on the moment Mz (out of the arch plane).

The main numerical analyses related to the ultimate limit state and serviceability limit state were performed as linear analyses, regardless that hangers can carry only tension force; modelling hangers as 'only tension' automatically change the analysis to nonlinear. Since in all of the considered load cases, all hangers were always in tension, running a linear analysis was a choice of savings of computational time. Additional analyses, like buckling, dynamic or nonlinear with initial imperfection of the arch, etc., were also executed, to cover all requirements for correct (to the best knowledge) design.

4 Bridge erection

The overall order of executed procedures during erection of Våla bridge is presented below.

- Erection of scaffolding for the deck.
- Casting concrete on the deck.
- Casting concrete part of the arch; see number 1 in Figure 7.
- Prestressing the deck with the tendons.
- Mounting the arch on the arch-scaffolding tower; see Figure 8.
- Mounting wind-truss.
- Casting end part of the concrete arch, see number 2 in Figure 7.
- Mounting of hangers.
- Prestressing of hangers.
- Disassembly of scaffolding.

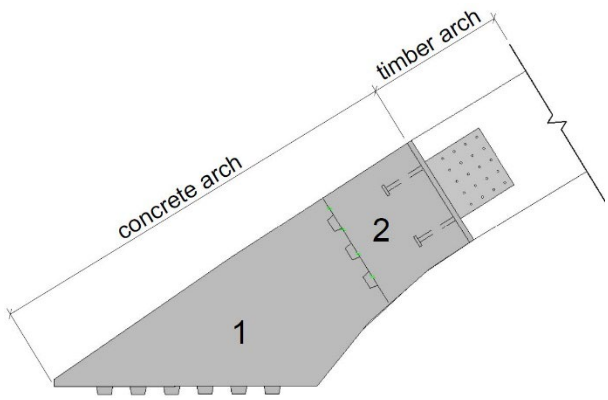

Figure 7 Concrete arch divided into parts according to the technological breaks.

Choice of the scaffolding for the deck was quite important. Since the deck in made of concrete, the scaffolding was necessary. Våla bridge is located above the river and a floodplain. It was assumed that no foundation should be places in the water. Due to limitation of free space between water level and underside of scaffolding, it was chosen to use two different systems of scaffolding. One system had temporary foundation on the edge of the river and spread above the water, while the second system was places directly on the ground, see Figure 8.

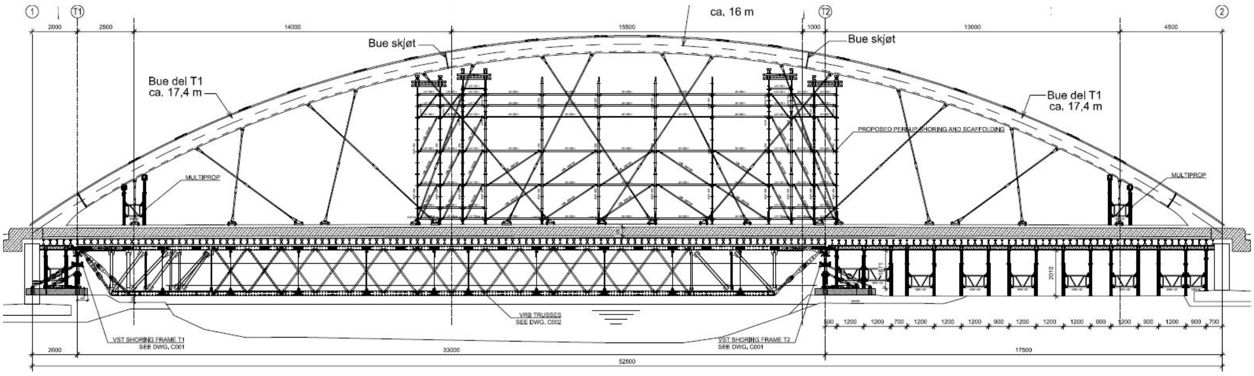

Figure 8 Outline of scaffolding system on Våla bridge

Such solution limits a span for the first type of scaffolding, which resulted in a smaller height of the scaffolding construction. However, it also leaded to the concentration forces in the point where two of systems were joining. Therefore, some ground settling was expected in this area, and responding local camber was formed on the deck. This camber was on the top to the already designed curvature of the deck which should compensate deformation of the construction form the self-weight. Unfortunately, real ground settling was smaller than calculated, and a part of the formed local camber become permanent. This situation, combined with building tolerances led to the challenging procedure of mounting and prestressing of hangers. In case of one hanger, the theoretical length between pin and pin was 7299 mm, while the distance measured on site was 67 mm shorter. Note, that each cable has tolerance of ± 50 mm, and while prestressing it should additionally shorten. Thus, prestressing of cables was an important and precise procedure in Våla bridge. It was executed in the iterative way, in three steps, which can be repeated in a loop. In the first step hangers were prestressed from the centre of the arch towards the ends. It was done simultaneously on both arches, see Figure 9. In the next step, hangers from one set, with inclination toward axis 2, were prestressed following direction from axis 1 to axis 2. Then, the other set, with inclination toward axis 1, was prestressed following direction from axis 1 to axis 2. Note, that one set of hangers consists of those hangers which incline in the same way. In the third step, procedure form step two was repeated, while assuming starting point in axis 2. In Våla bru the required level of prestress was achieved already in the step two, while the step tree was used just for small adjustments. Prestressing took circa one day. Additional verification of hangers' prestress was done around one week later. Prestressing of hangers was the last major work made before scaffolding was removed. Figure 10 and Figure 11 present the bridge under construction.

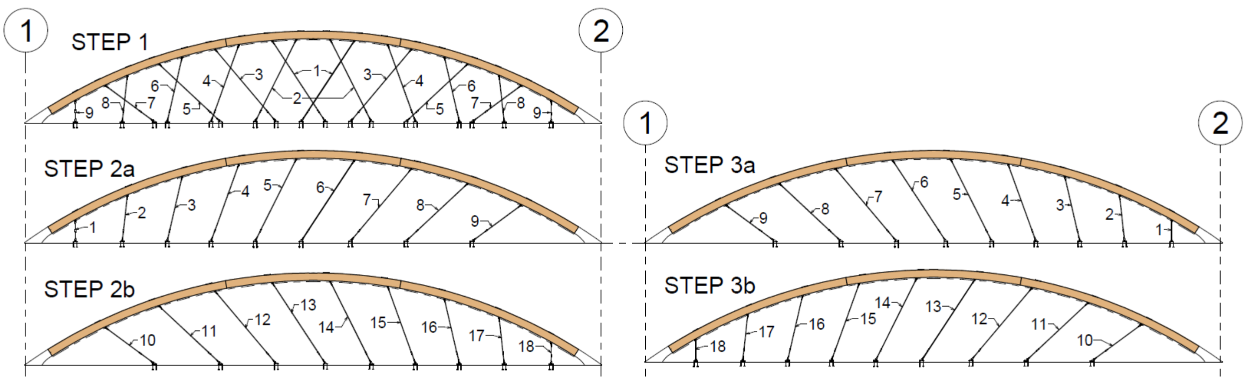

Figure 9 Prestressing procedure of hangers

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Figure 10 Våla bru under construction (photo: H. E. Wedum)

Figure 11 Våla bru – scaffolding on flood-plain (photo: H. E. Wedum)

5 Conclusions

This paper summarizes procedure of designing Våla footbridge. In the first part, the simplified procedure of choosing an 'semi-optimal' network pattern was presented. The procedure is based on visual grading of 2D-outline of patterns and studying force distribution in hangers from self-weight. In second part of the paper, some designing aspect of the bridge were described. Selected challenges from the building site and used techniques were presented in the final part of this paper.

The paper shows the importance of right choice of the network patten, and that the network arch timber bridges have a potential for medium span footbridges. Figure 12 and Figure 13 present the completed bridge.

Figure 12 Våla bridge (photo: H. E. Wedum)

6 Acknowledgement

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Figure 13 Våla bridge (photo: P. K. Ekeberg)

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