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SKYTEBANEN BRIDGE – A TIMBER TRUSS BRIDGE WITH AN INTERMEDIATE SUSPENDED CONCRETE DECK

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ABSTRACT: Skytebanen bridge is a timber truss bridge built for the Norwegian Public Roads Administration in 2019. It has a single span length of 40.0 m and a width of 5.0 m with one notional traffic lane. It is constructed with two dual pitch timber frames, with a concrete deck between. The timber frames are mounted in an asymmetrical manner which gives an irregular aesthetical expression. The timber frames have a total height of 10.8 m. The bridge combines timber in its primary load carrying system with concrete deck and steel floor beams. In this paper some aspects of special interest from the design perspective are highlighted.

KEYWORDS: Timber truss bridge, Concrete deck, Stainless steel, Dowel type joints, Aesthetics, Norway

1 INTRODUCTION

This paper gives is a brief description of the Skytebanen bridge. Furthermore, it addresses some topics that can be of special interest for designers and architects working with timber bridges.

Figure 1: *Skytebanen bridge. Photo: Jan Inge Larsen*

2 STRUCTURAL CONCEPT

2.1 BEHIND THE DESIGN

The bridge is crossing highway E6 in Grane municipality, just south of the polar circle, in the northern part of Norway. Grane has a considerable wooden industry, and the nearest producer of wooden trusses is located just a few kilometres from the bridge site. The surroundings are scenic, located between two national parks. As a future portal to Grane it was a strong desire for a wooden bridge, and the choice of a truss bridge was partly because of the link to the local industry, and partly because it offered some interesting architectural opportunities.

Figure 2: *The bridge seen from the east side. Photo: Jan Inge Larsen*

2.2 ARCHITECTURAL EXPRESSION

The architectural design of the bridge was done by Karen Hatleskog Zeiner, Multiconsult, who described the idea behind as following:
"The design is a classic truss bridge with a twist. The trusses on each side of the bridge are mirrored, which creates a dynamic appearance, that changes depending on the point of view. The shape of the bridge reflects the surrounding mountains.
The lighting plays an important role, especially in the polar dark period, which lasts from November to February. The lighting emphasises the truss construction, and makes the bridge visible from afar, creating a landmark on the E6."

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Figure 3: Skytebanen bridge by night. Photo: Jan Inge Larsen

To give the construction a simple aesthetical expression, it was emphasised that the underside of the bridge should look as smooth as possible, with no visible beams underneath.

2.3 TECHNICAL PREMISES

2.3.1 General regulations

All relevant Eurocodes as well as directions from the Norwegian Public Roads Administration (NPRA) valid in 2016 was applied in the bridge design.

2.3.2 General design - common solutions

The bridge is founded on drilled steel-pipe-piles supporting the concrete abutments. Horizontal forces are handled by friction-plates at the bottom of the abutments.

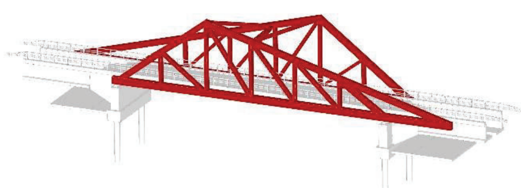

Figure 4: Overview of the complete bridge

The superstructure is a timber through truss with the deck located at the level of the bottom chord. The static system is based on a simple statically determinate system which is easy to check by simple means. However, some modifications are made to the system, like two pinned bearings, and a partly fixed bridge deck, resulting in a somewhat more complex system. Nevertheless, the horizontal stiffness of the abutments is very low, implying that the system is acting mainly as a simply supported truss.

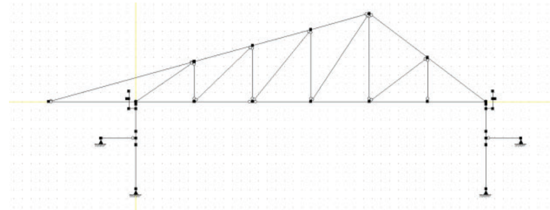

Figure 5: Basic static system

Stability of the upper chord against wind and buckling is mainly provided by a stiff connection between the floor beams and the vertical posts. The bridge is also provided with a top strut to transfer wind loads between the trusses, in addition to two upper lateral bracings with mainly aesthetical purposes. All truss members are made of homogenous glulam GL30h [1] to ensure that the dowel based connections have sufficient strength. The truss joints are mainly based on slotted in steel plates with dowels, a method frequently used for timber bridges in Norway, with detailed design rules given in [2]. All glulam parts are treated with copper preservatives in addition to creosote. All horizontal or sloped surfaces are protected against rain with zink fittings.

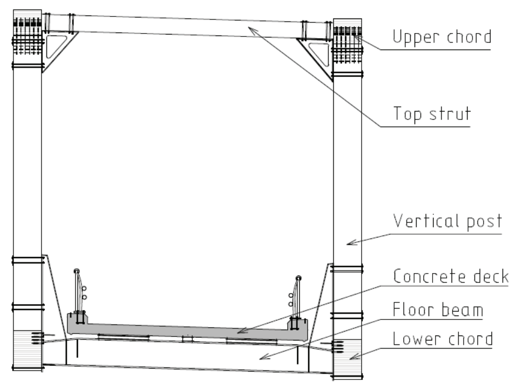

Figure 6: Cross section of the bridge

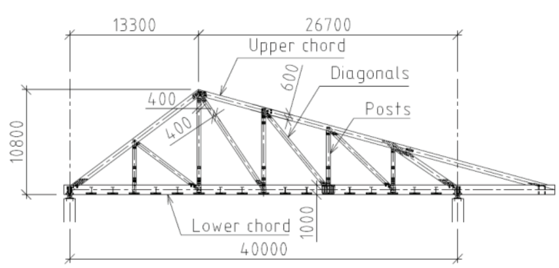

Figure 7: Side elevation of bridge

2.3.3 Bridge deck material

Most timber bridges in Norway are built with stress-laminated timber decks with waterproof membrane and asphalt. During preliminary design there was a general discussion regarding the durability of stress-laminated timber decks, and the client was concerned that a service

life of 100 years could not be achieved. Hence, it was decided that the bridge should be designed with a reinforced concrete deck.
A concrete deck is a robust solution, being durable and easy to maintain. However, a stress laminated timber deck may be a better solution for many timber truss bridges. In this particular case, the span width between floor beams could have been made larger due to lower self-weight. Hence, floor beams could have been supported at truss joints only, instead of also in-between. Moreover, a timber deck induces less constraining forces due to temperature and moisture fluctuations.
With the prohibition of creosote from 2023 it is expected that Skytebanen is not the last wooden bridge with a concrete deck in Norway.

2.3.4 Suspension of the bridge deck

The typical solution for timber truss bridges in Norway is to arrange the bridge-deck on transverse steel beams suspended below the truss joints in the lower chord, as shown in Figure 8.

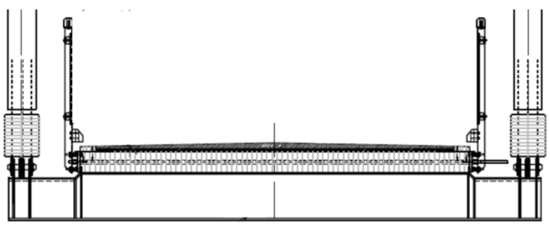

Figure 8: *Typical solution based on stress laminated deck and beams suspended under the lower chord*

For architectural reasons the distance between truss joints was chosen to be 6,67 m. In order to limit the required thickness and hence weight of the concrete deck, it was decided to use floor beams of steel every 2,22 m, i.e. with 2 supports between the truss joints, introduction bending moments in addition to truss forces in the lower chord. As outlined in Ch. 2.2 the floor beams were placed between the lower chords instead of underneath them, as illustrated in Figure 9.

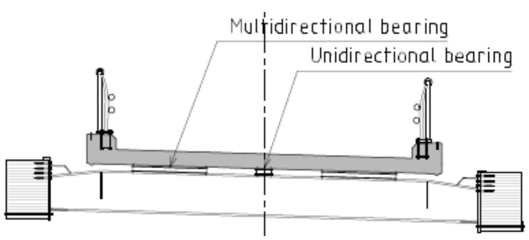

Figure 9: *Beams connected with lag screws to the lower chord*

In retrospect it is acknowledged that there are good reasons for suspending the floor beams underneath the lower chord, as shown on Figure 8, and that this design is easier to build and maintain. If there are architectural reasons to hide floor beams, this might be better solved by glulam panels mounted on the outside of the beam ends.

3 TECHNICAL CHALLENGES

Choosing a concrete deck combined with hidden floor beams led to some challenges that we had to overcome in the design. These challenges will be discussed in the following.

3.1 DIMENSIONAL CHANGES

Compared to concrete, timber has other properties for temperature, creep, shrinkage and moisture fluctuations. Thus, wood and concrete may be challenging materials to combine.
The effect of temperature on the strength and stiffness of wood is described, e.g. by [3] and [5], indicating a reduction of 2-5% for the maximum temperature. Temperatures above 20 °C for many hours will rarely occur at the bridge site. High temperatures will usually reduce the moisture content, and this will counteract the temperature effect. For temperatures below approximately 20 °C the strength and stiffness will be higher than the values used in design. Hence, the effects from temperature on stiffness and strength were ignored. Elastic deformations and creep were handled by the structural analysis and subsequent modifications.

3.1.1 Moisture content

In addition to dimensional changes, moisture fluctuations affect stiffness and strength of wood. The effect on strength and deformations was handled by estimating climate factors according to [2].
The moisture content of wood is highly dependent on the relative humidity in the environment, and not so much on the temperature [3], [4]. Based on conclusions in [6] an equilibrium moisture content of 12,5 % was assumed. To our knowledge there is no recognized method to determine the moisture fluctuations in massive wood constructions. Based on [6], [7] and [8] a maximum variation of ± 8 % was assumed, which resulted in a total free elongation of ± 16 mm for the lower chord in the length direction of the bridge.
Dimensional changes perpendicular to grain are much larger than in the longitudinal direction. Based on [7] and [8] the free dimensional change of the lower chord was calculated to ± 8 mm vertically. This affected design of the large joints in the lower chord, as further described in chapter 3.3.

3.1.2 Shrinkage in concrete

The total free shrinkage strain in the deck was, based on [9] and 80 % RH, calculated to be - 9 mm (i.e. contraction).

3.1.3 Temperature

Temperature expansion was estimated according to [8]. The free thermal expansion of the lower chord was calculated to be + 5 mm and - 8 mm in the length direction of the bridge. The thermal expansion of the concrete deck was calculated to be + 8 mm and -17 mm.

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3.1.4 Combination of strains due to temperature and moisture

How effects from temperature and moisture expansion should be combined are not clearly described in the Eurocodes. It was assumed that the highest temperature will occur simultaneously with the lowest moisture content. This is conservative for the connection between deck and lower chord, because it gives the highest difference in movement between concrete deck and lower chord. For the design of the lower chord this will not be conservative, as the bridge is fixed at both bearings. However, temperature effects will give small constraint forces due to flexible abutments.

Table 1: *Comparison of different combinations of temperature and moisture content, and effect on chord elongation*

Load combination	Elongation (mm)
Lower chord: Lowest temperature occurring simultaneously with the highest moisture content.	8
Lower chord: Lowest temperature occurring simultaneously with the lowest moisture content.	-24
Bridge deck: Lowest temperature occurring simultaneously with maximum shrinkage.	-26

The assumption that high temperature/low moisture content and low temperature/high moisture content will occur simultaneously was questioned by the third party controller. Probably the most accurate assumption is somewhere in between. However, the conclusion is, regardless of how this is treated, that the structural integrity is sufficient.

3.2 CONNECTION DECK – FLOOR BEAMS

As described in chapter 3.1 the deformations in deck and lower chord are quite different. Without any measures introduced, this would have resulted in significant constraining forces. Based on discussions with NPRA it was concluded to install bearings between deck and floor beams, except for the seven beams at the centre of the main span, see Figure 9 and Figure 10. It is admitted that this solution is rather costly, and also introduces some challenges due to maintenance of the bridge.

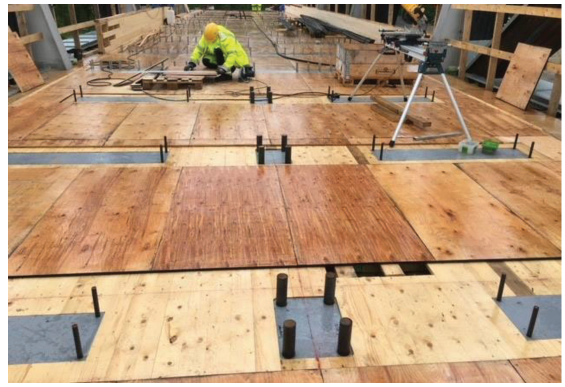

Figure 10: *Bearings visible in the formwork shell. Photo: Viggo Jakobsen, Consto Nord AS*

3.3 CONNECTION FLOOR BEAMS - TRUSS

The connection between floor beams and the lower chord was designed with laterally loaded lag screws. Since the load is applied eccentrically it was also installed bolts in the bottom of the beam to reduce the action of torsional moments on the lower chord. Since the distance between the lag screw group and the lower bolts where quite big, the lower bolts were placed in vertically oversized holes to enable the wood to expand and contract due to moisture content, as outlined in Ch. 3.1.1.

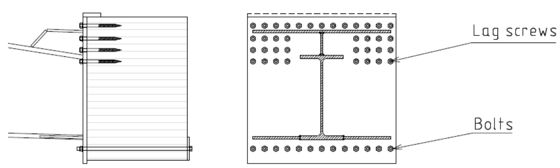

Figure 11: *Detail of connection floor beam to lower truss*

To ensure horizontal stability of the truss against wind and buckling a stiff bracket between each floor beam and vertical post was arranged. The bracket was designed to transfer bending moments only. Normal forces were handled by the dowel based connections in the truss, see Figure 6. Movements of the wood were enabled with oversized bolt holes also here.

3.4 CORROSION

It was decided to use acid proof stainless steel for all steel structures, instead of steel with a duplex coating consisting of hot-dip galvanizing and powder coating.

The background for the material choices is the required service life of 100 years, with low need for maintenance. Moreover, the design of the detail with the large steel-plate connected to the lower chord of the timber truss has some disadvantages regarding maintenance of a coating system:

- The plate has a large surface that is not available for inspection and maintenance
- Cracking of wood due to drying, in combination with rain and wind, may cause water to enter

- behind the steel plate. The coated plate may then be exposed to moisture, which over time will increase the corrosivity and the risk of steel degradation
- The copper preservatives used to protect the wood are corrosive to steel if the coating is damaged or degraded over time

Figure 12: *Floor beams connected to lower chord. Photo: Viggo Jakobsen, Consto Nord AS*

4 CONSTRUCTION

The bridge was built for the NPRA, by Consto Nord AS. Glulam and steel constructions were delivered by Moelven Limtre AS. The bridge parts were produced in factory and the trusses assembled on site, before each truss and the transverse beams were erected by crane. The concrete deck was casted in-situ after erection of the trusses.

Figure 13: *Trusses after erection. Photo: Viggo Jakobsen, Consto Nord AS*

5 EXAMINATION AFTER TIMBER TRUSS BRIDGE COLLAPSES

Two major timber truss bridges in Norway have collapsed in recent years, Perkolo (2016) and Tretten (2022). The paper “Design flaws on Norwegian Timber Bridges“ [15] summarizes some important findings and conclusions from the investigations after the collapse of Perkolo bridge. After the collapse of Tretten bridge, the NPRA have examined 14 timber truss bridges, among them Skytebanen. For Skytebanen bridge the examination concluded that there were some deviations/uncertainties in the design report, especially related to the handling of temperature and moisture variations. Moreover, it was pointed out some uncertainties regarding the rotational stiffness of the floor beams. The choices of climate class and strength modification factors were however deemed conservative. It was concluded that the bridge safety was satisfactory without any reinforcements or restrictions, and Skytebanen bridge is now, as one of the first of the investigated bridges, reopened for traffic [14].

6 CONCLUSIONS

It is concluded that using a concrete deck for timber truss bridges works well. It can also be noted that placing the floor beams between the lower chords, instead of underneath, is fully possible.

After the design of Skytebanen bridge was started, Norway has experienced two collapses of timber through truss bridges. Regardless of the reasons, both cases have reminded us that such bridges often are fracture-critical, and thus vulnerable to unforeseen actions, deficiencies and deviations during design and construction. On this background it is concluded that for these bridges a simple and clear static system which is easy to verify, build and maintain should be preferred.

Figure 14: *Skytebanen bridge at dawn. Photo: Jan Inge Larsen*

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