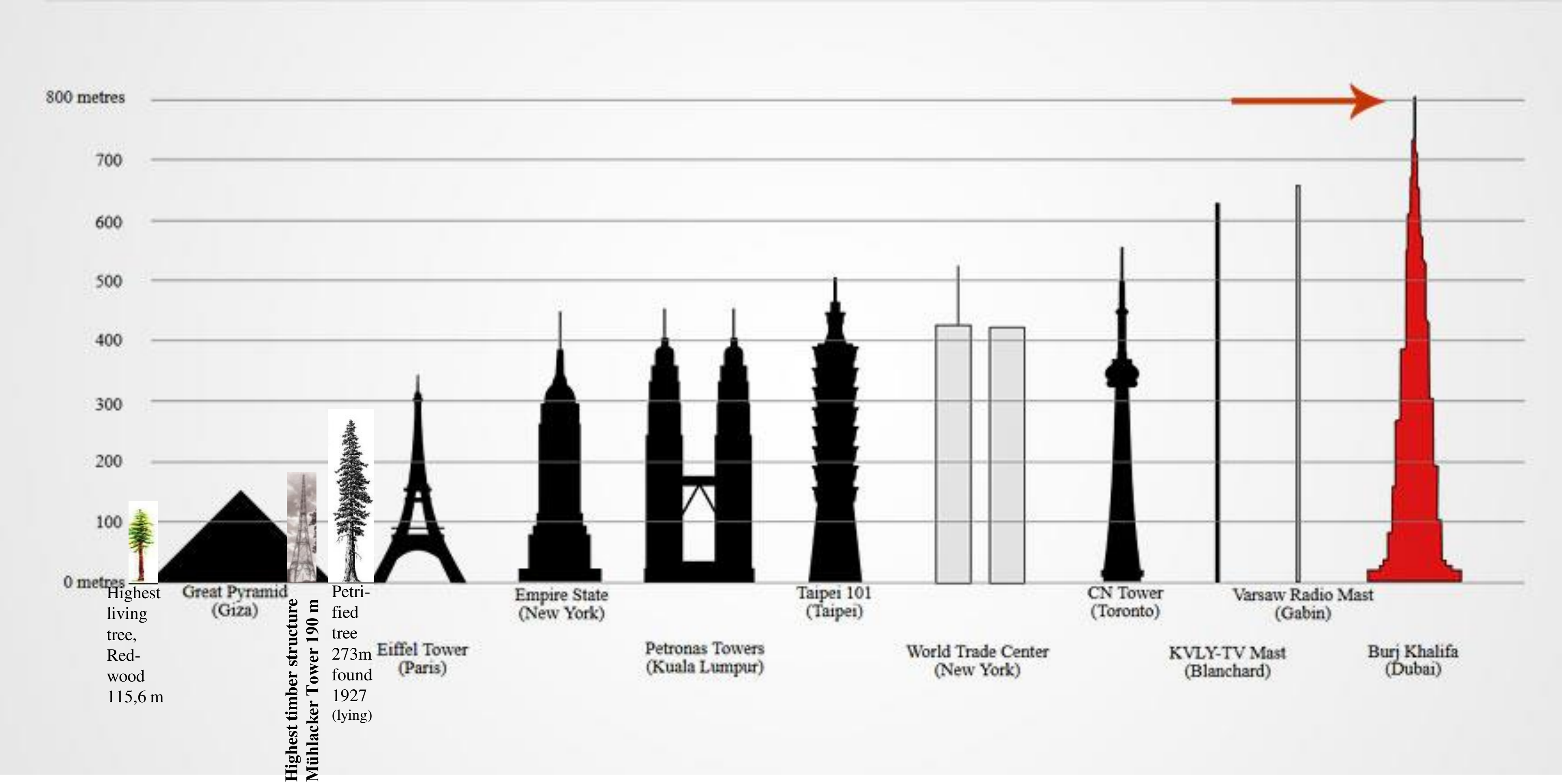
Long Span Timber Structures with Composite Action – from disaster to success

Nils Ivar Bovim
Norway

World’s highest buildings and trees

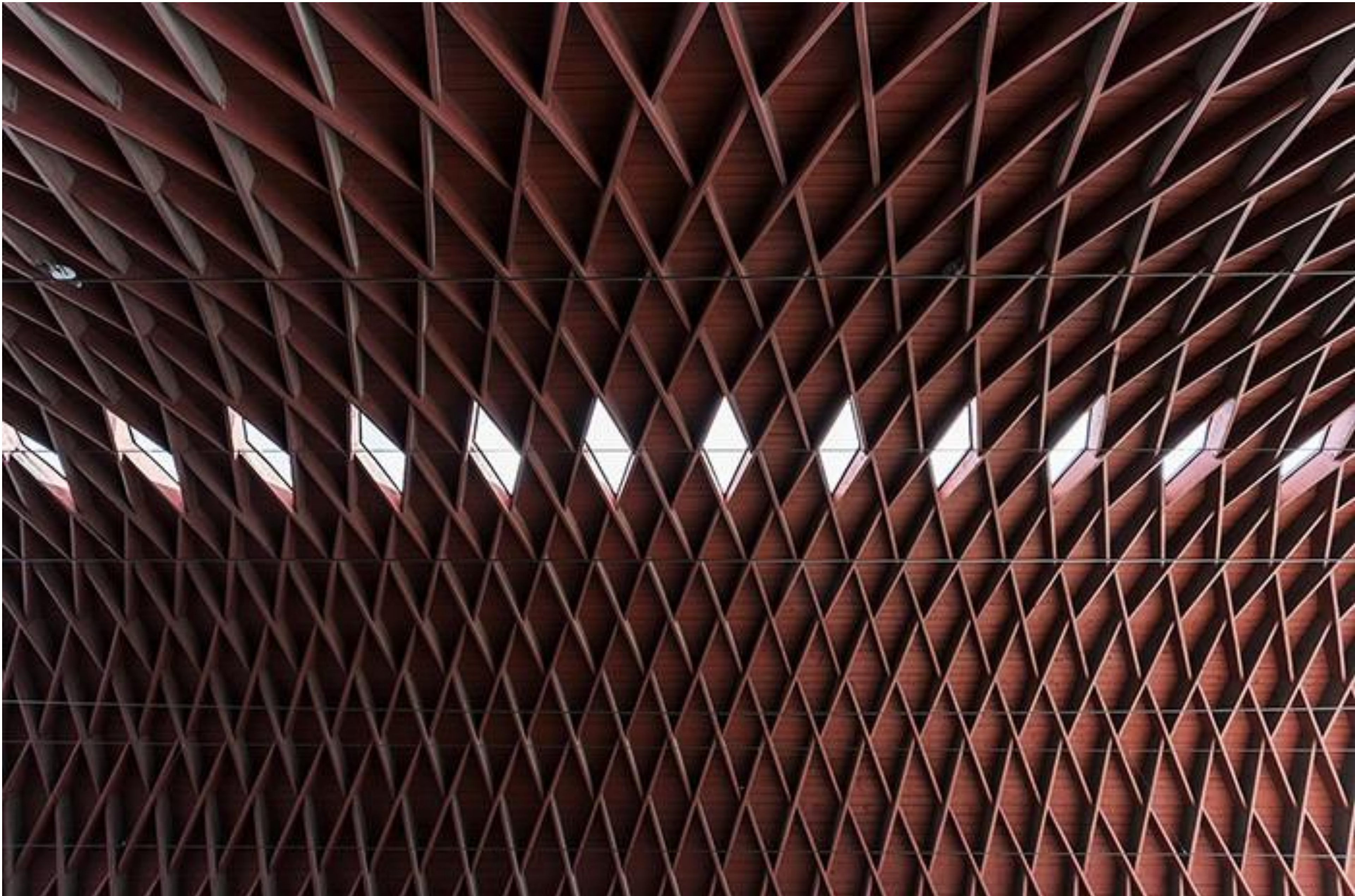


Composite action is the only solution to increase the size of timber structures made from from small pieces of wood

- Opened about 1930
- «Barrel structure» made of short timber pieces with composite action

Nørreport Station, Copenhagen

Bottom-up view of Barrel arch, Nørreport Station



Nørreport Station, Copenhagen

Mühlacker transmission tower made of timber

In 1933-34, a 190 m high wooden tower was built - the tallest structure ever built !!

The radio tower was built for antennas with transmission power of 100 kW.

On April 6, 1945, the wooden tower and the masts carrying the system of T-antennas were blown up by the SS to prevent its capture by the Allies in World War II.

World’s biggest timber structure: Hangar for 8 airships

- Hangar for 8 airships built during 2. World War,
- Lack of steel during the war forced the use of timber in the hangars
- Span of structure: 115 m
- Length of structure: 340 m
- Height of structure: 52 m
- Contains ≈ 1 million board meter of fireproofed Douglas fir
- Held together by 79 tons of bolts and washers and 30 tons of ring connectors

Several disasters:

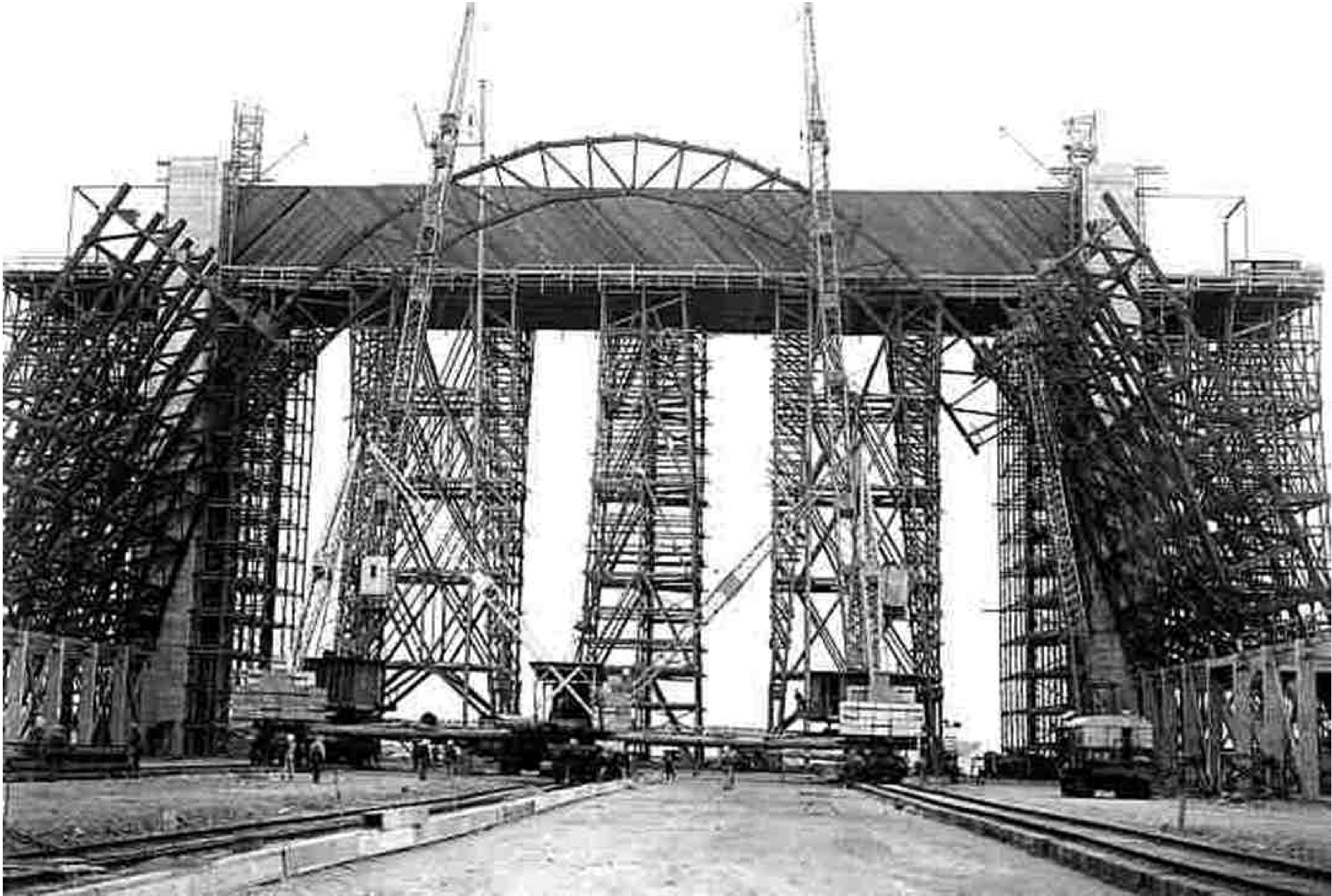
- Twice in early 1943, gusty winds collapsed the partially built hangars
- One in Oregon was destroyed by fire
- **Fifteen other** airship hangars - only five of which survived - were built from the same design.

Now Tillamook Air Museum, Oregon US

Picture from
2. World War

World’s biggest timber structure: Hangar for 8 airships

World’s biggest timber structure: Hangar for 8 airships



World’s biggest …: Detail of structure

Generally, 3 main reasons for collapse of structures

1. Planning and design
2. Construction / building phase
3. Lack of maintenance, use and others

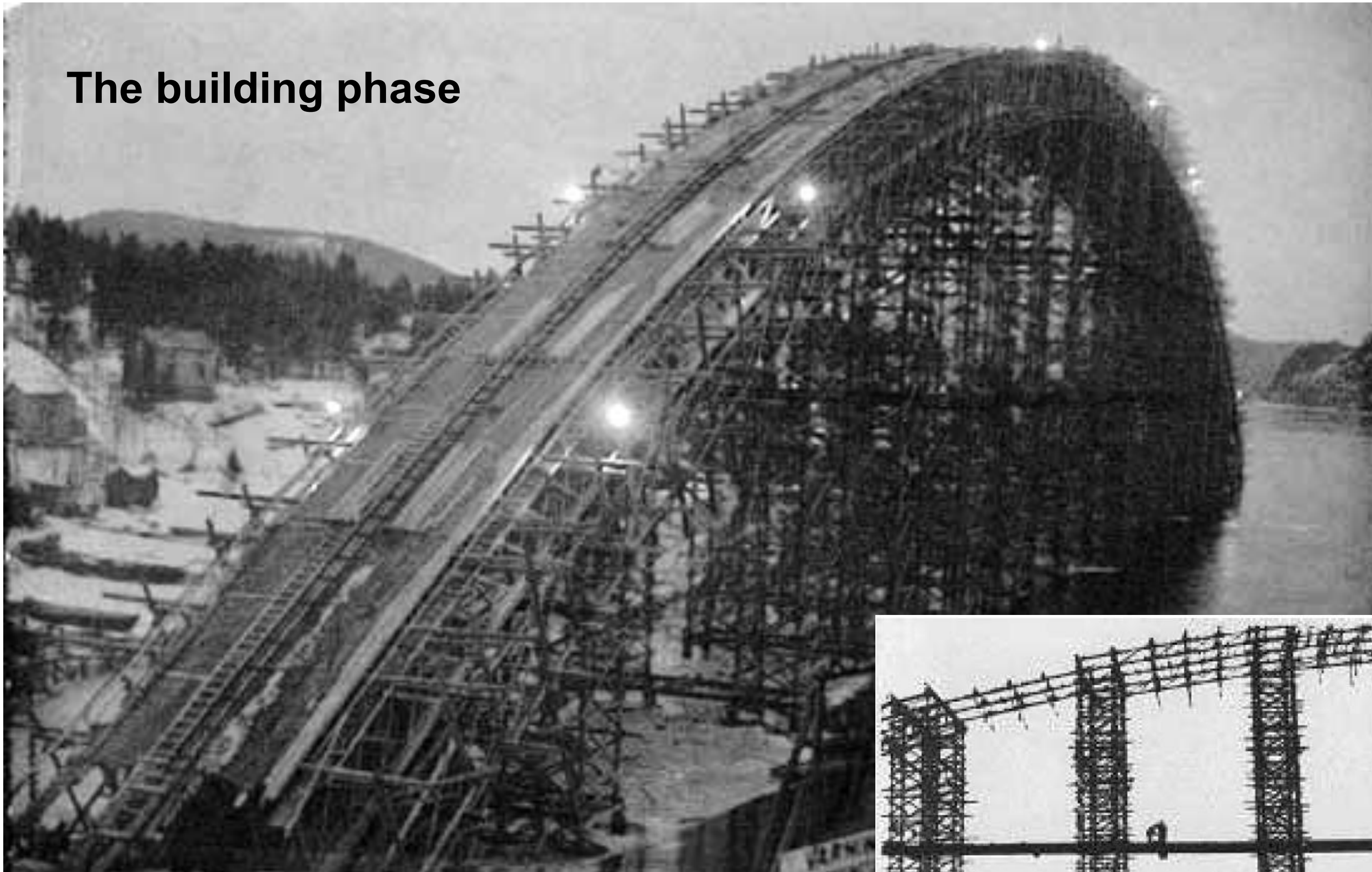
Reasons No.1 and 2 are of about the same order, No.3 relatively less.

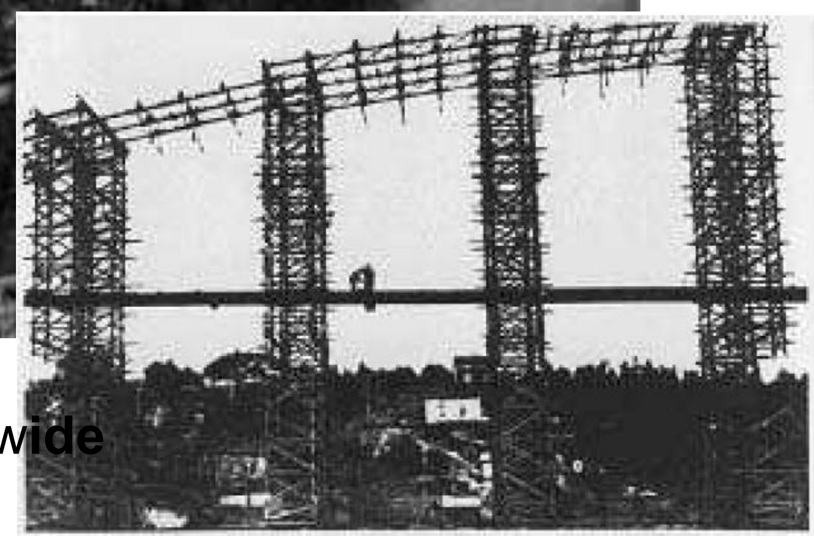
About **60% of the failures occur during the building phase**. Even if the problem is planning or design, the failure often occur during the building phase.

Failures where people were **killed or injured** is relatively worse, **65-70% occurs during the building phase**.

Ref.: *Design of safe timber structures – How can we learn from structural failures in concrete, steel and timber?* Frühwald&al, Lund Institute of Technology, 2007

Probably the most spectacular timber structure in history



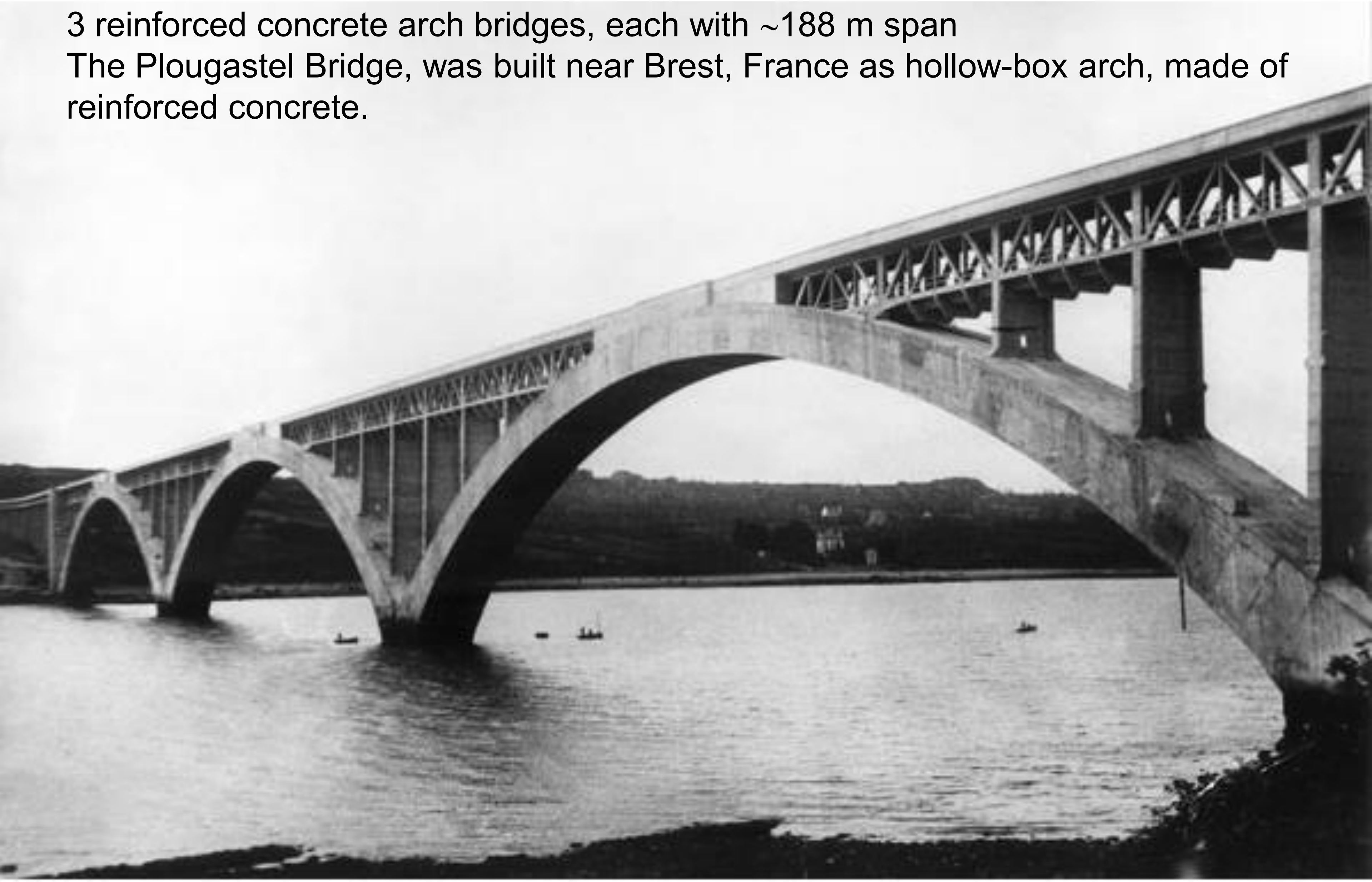


Formwork and scaffolding for Sandö Bridge, Sweden 1938-39. Arch span 264 m, 11,1 m wide

The highest scaffolding tower was 37 m.

The idea to Sandø bridge probably came from the france bridge Pont de Plougastel built 1926 – 1930

3 reinforced concrete arch bridges, each with ~188 m span
The Plougastel Bridge, was built near Brest, France as hollow-box arch, made of reinforced concrete.



The formwork was built with steel framework

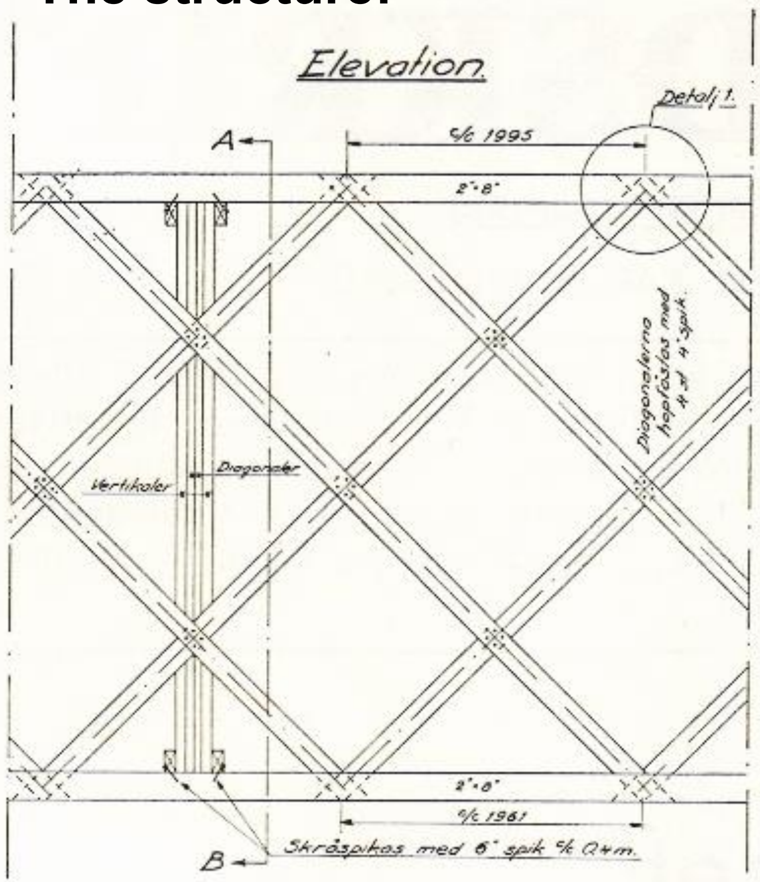
Plougastel bridge
Formwork cladding of diagonal timber boards

Pont de Plougastel (Finistère)

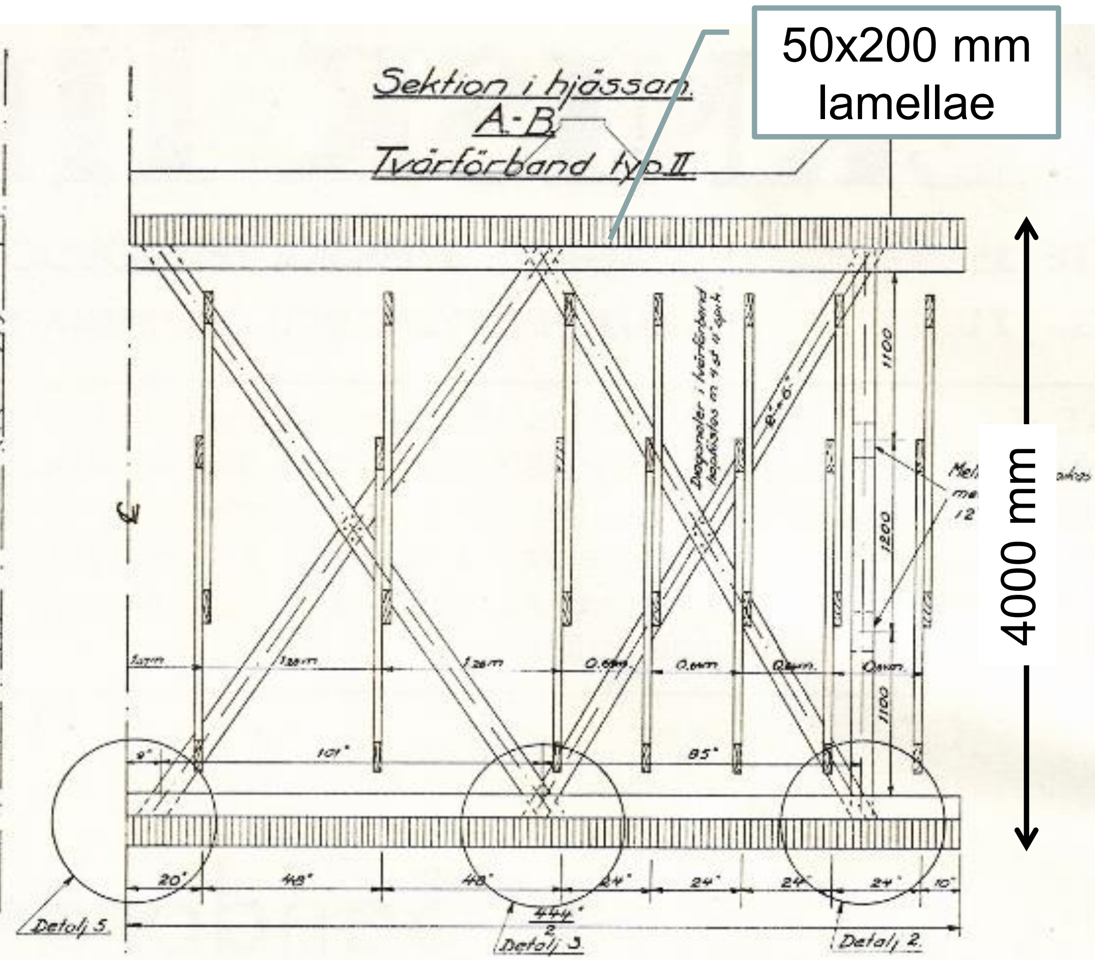
The formwork was reused for the 3 arches

Probably the most spectacular timber structure in history

The structure:



Longitudinal section



One half cross-section with stiffening diagonals

Formwork and scaffolding for Sandö Bridge

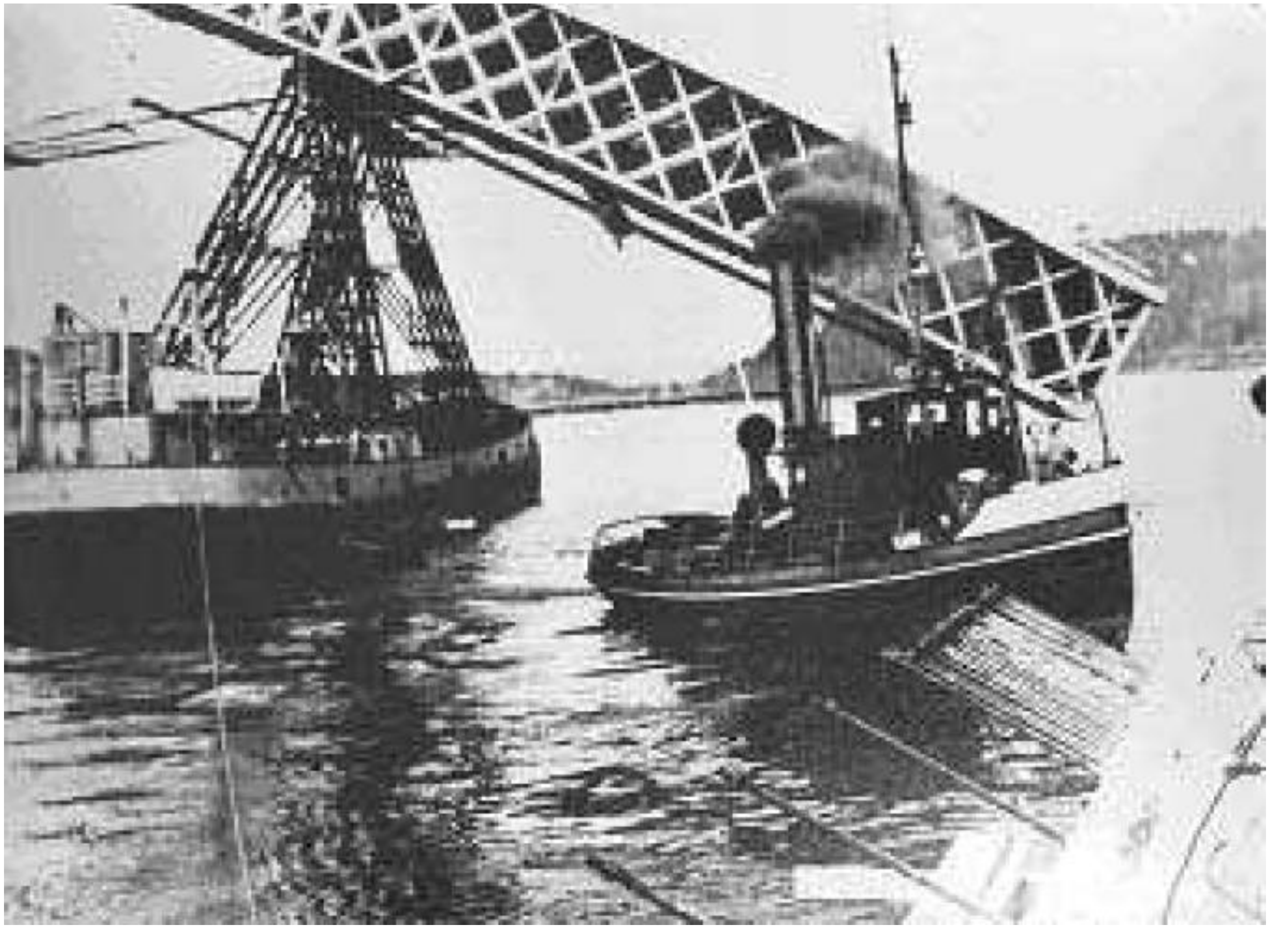
Upper and lower chord is parallel nailed (12″ nails) massiv wood structure with nailed diagonals in between. **Thickness of the chords is only 200 mm!**

Not only the most spectacular timber structure, also the most spectacular transportation of such a structure

Formwork and scaffolding were buildt on the riverbank

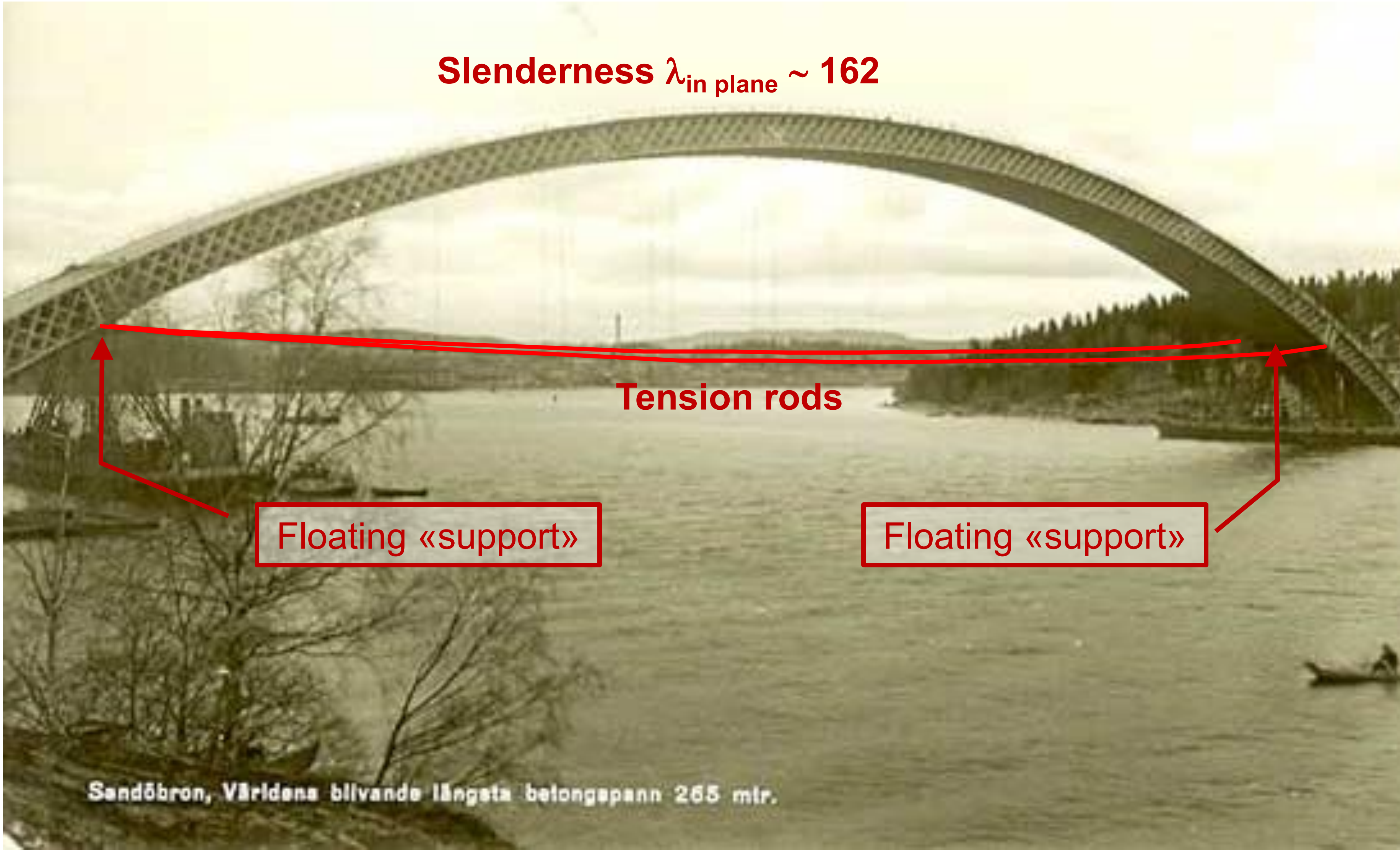
The scaffolding towers were removed an **the whole structure transported across the river with boats** at the 18th of May, 1939

Probably the most spectacular timber structure in history



Picture taken just before landing one end of the timber arch

Probably the most spectacular timber structure in history



The operation was a success and casting of the concrete arch could start.

Probably the most spectacular timber structure in history

30. August, 1939 - only 12 m from finishing the concrete casting (!) -
a huge sound was heard and the complete structure collapsed

Probably the most spectacular timber structure in history

About 40 workers followed the bridge into the water -

18 died

Next day 2nd world war started,

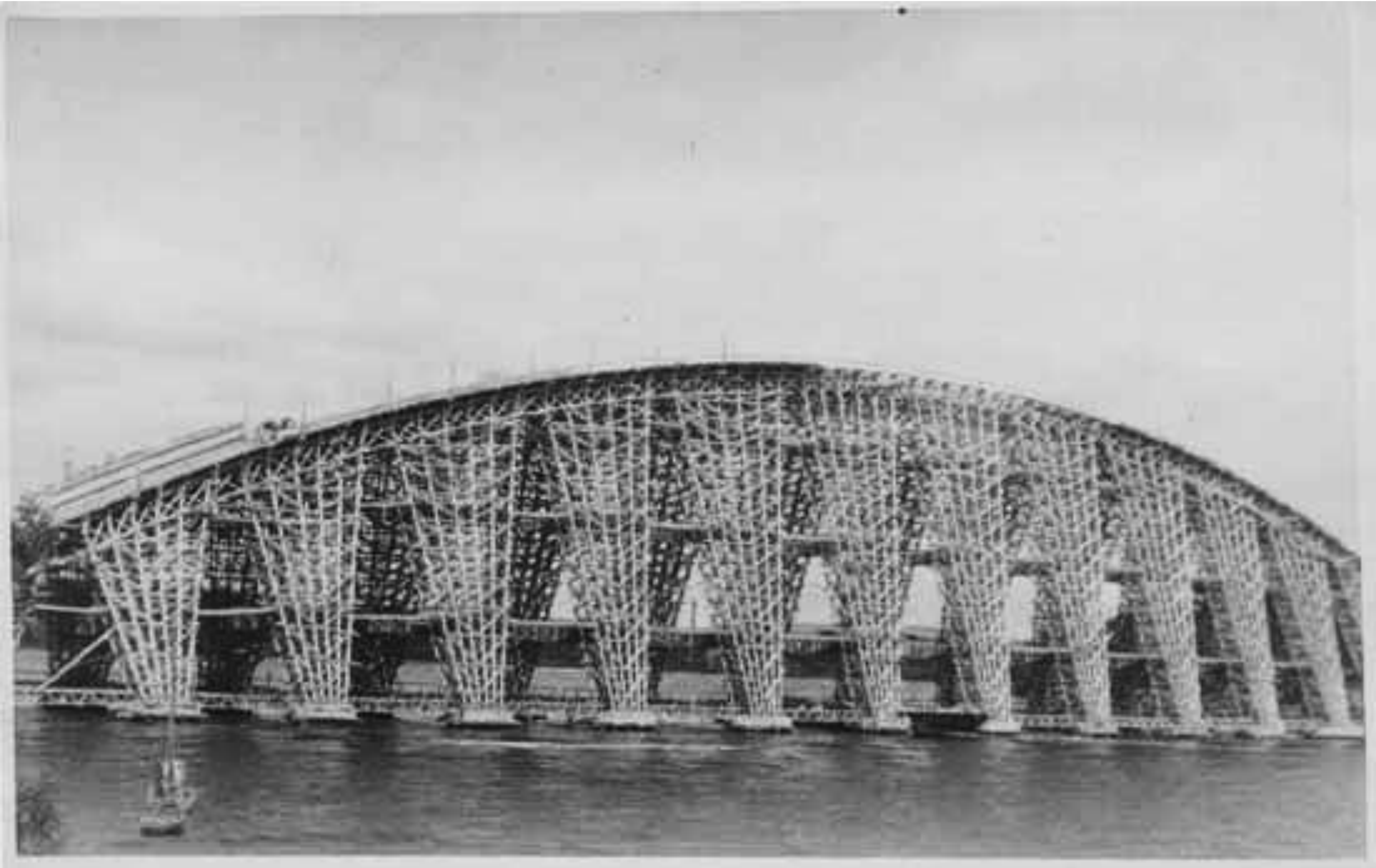
leaving one of the biggest work accidents i Sweden as a short note in the newspapers.

Witness descriptions indicated buckling in vertical direction (in plane) of the whole section as the failure mode.

The investigating committee stated that the failure was caused by insufficient strength/stiffness of the transverse bracing between the two flanges.

Later investigations have proposed lateral instability of the arch as responsible for the failure

The Sandö Bridge was completed and opened in 1943 using a new scaffolding system with poles through the riverbed.



The Sandö Bridge was completed and opened in 1943.
The worlds longest spanning concrete arch bridge until 1964

The Sandö Bridge was completed and opened in 1943.

From Wikipedia, about bridge failures and Sandö bridge:

Sandö Bridge	Kramfors,Ångermanland	Sweden	31 August 1939	Concrete arch bridge	Collapsed during construction	18 killed	Complete loss of the main span	Did not receive much media attention as the Second World War began the next day. The bridge was finished in 1943 as the longest concrete arch bridge in the world until 1964.

Learning from failures are especially of interest for new generations of engineers
and for developement of new and better bridge design,
and even for development of timber structures in general!

However, knowbody has concluded what caused the failure of Sandö formwork in reality.

Instability of timber structures is a real problem – as for other materials

Instability is a very dominant failure mode according to a comprehensive Swedish/Finnish report from Lund University, 2007

Collaps or failure was caused by insufficient or absent bracing leading to buckling and material failure

Failure mode	Percentage
Instability	30
Bending failure	15
Tension failure perpendicular to grain	11
Shear failure	9
Drying cracks	9
Excessive deflection	7
Tension failure	5
Corrosion of fasteners / decay	4
Withdrawal of fasteners	3
Compression	2
Other / unknown	21

Ref.: *Design of safe timber structures – How can we learn from structural failures in concrete, steel and timber?* Frühwald&al, Lund Institute of Technology, 2007

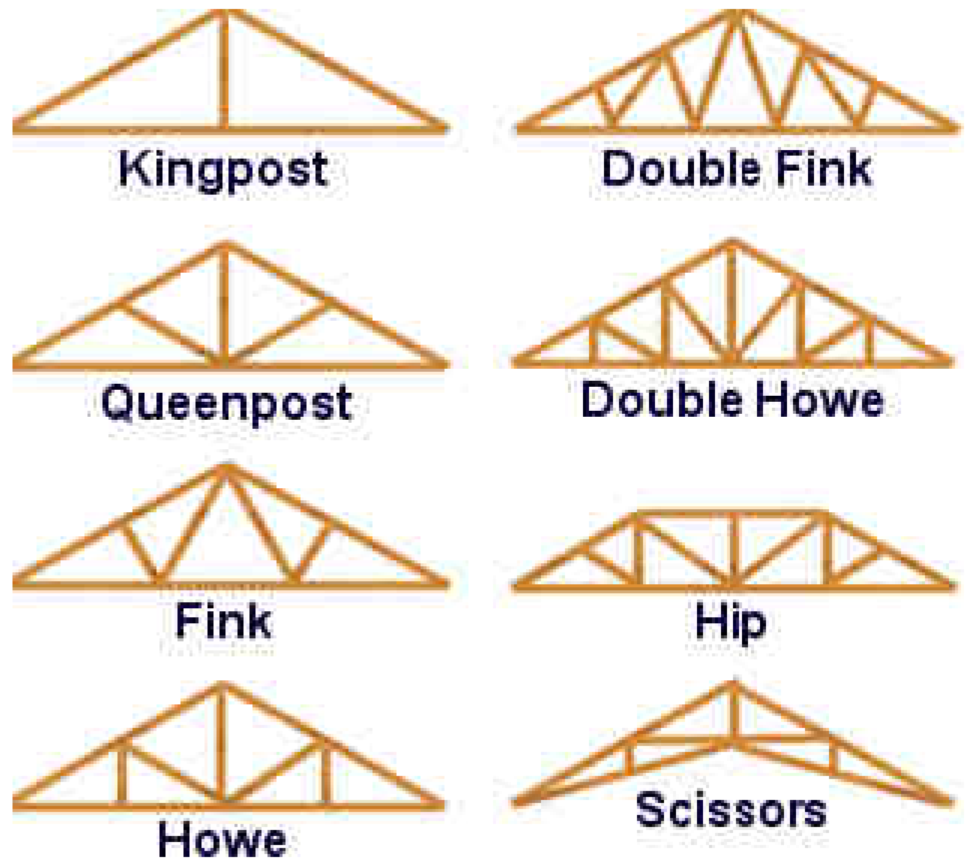
Stability failure - lack of bracing

Photo taken about 10 seconds before the 52’ scissor trusses collapsed.
There was no wind or snow loads, only dead load from the trusses!
The top chord is buckling from a lack of proper top chord bracing

Challenges for scissor trusses

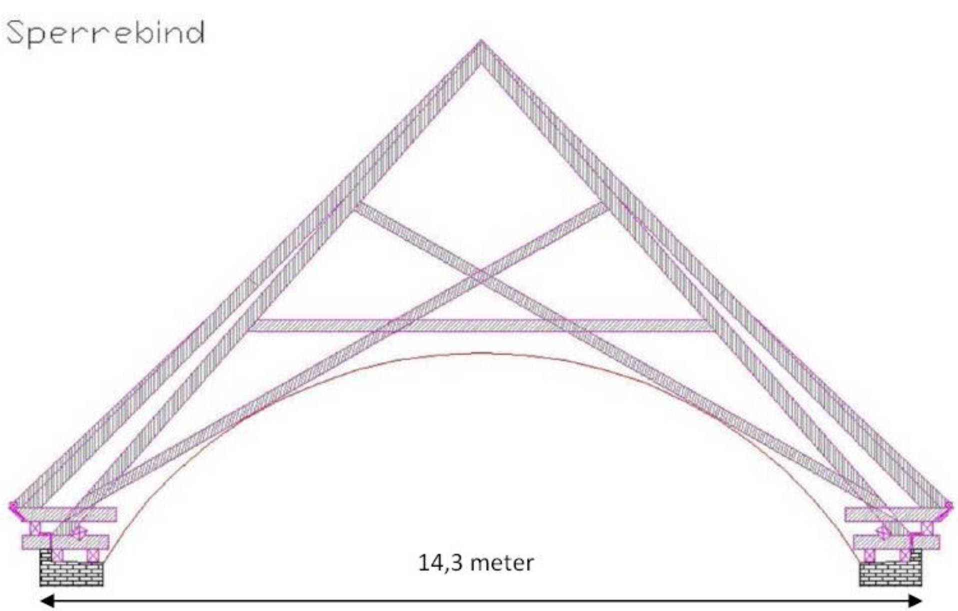
Compared with trusses having horizontal ceiling

- the structural height of scissor trusses are less (for identical roof pitch)
- the axial forces in upper and lower chord are significantly higher and lateral bracing of the chord even more important
- the center of gravity is significantly higher positioned, resulting in higher erection forces and need for more extensive bracing during construction
- horizontal forces in the supports tend to **push the supports outwards**



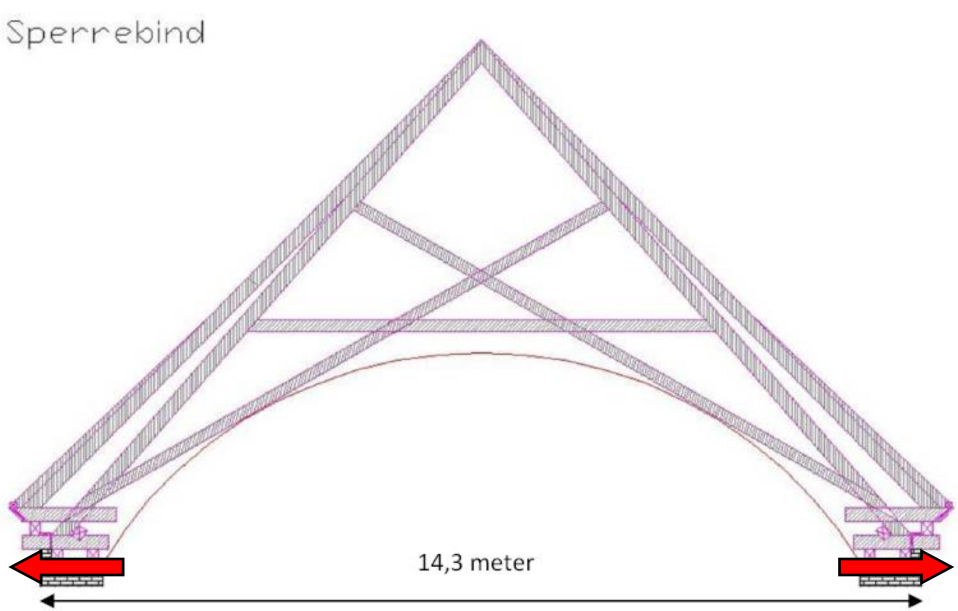
Example Oslo Cathedral (1694 -)

- Vaulted ceiling and scissor trusses
- The bracing system was cut (!) because a new organ demanded more space



Oslo Cathedral (1694 -)

- Vaulted ceiling and scissor trusses
- The bracing system was cut (!) because a new organ demanded more space
- Horisontal reaction forces tend to push external walls outwards (70 mm)



Lack of stability in the construction phase

Only a minor part of the bracing system was mounted!

It seems too late to install this stabilizing boards!

Here we have the rest of stabilizing sheating!

Short purlins – weak nailed joint on every truss

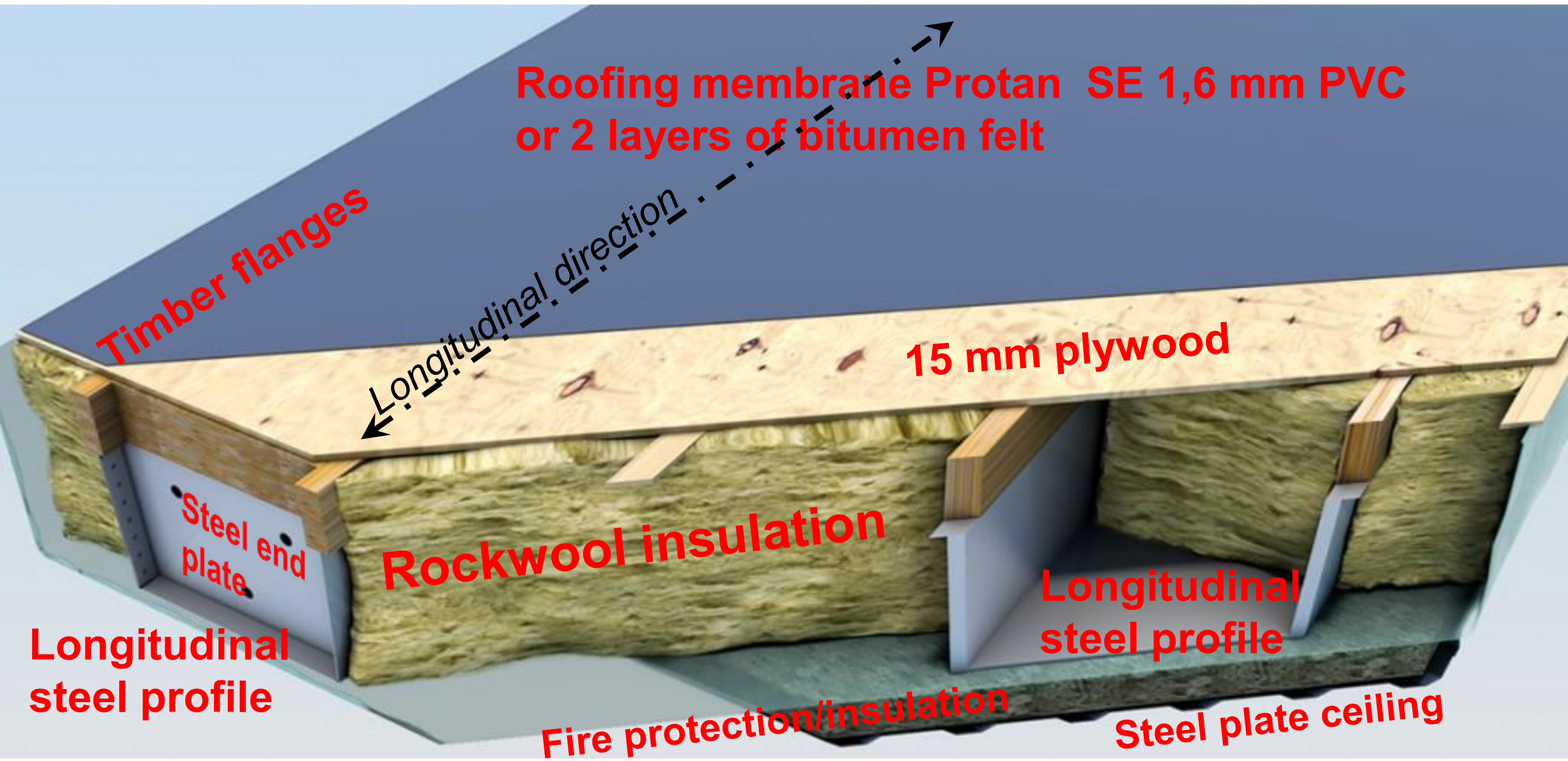
Lett-Tak roof panel system with composite action of plywood, timber and steel

- **Located in Larvik, Norway**
- **Yearly production capacity 300 000 m²**
- **Advanced product, full control from production to finnished roof**
- **Several projects also in Sweden, Denmark, Iceland, Germany**
- **Dead weight 0,4 - 0,5 kN/m²**
- **Insulation: U-values from 0,18 – 0,07 [W/m²K]**
- **Fire resistance up to 90 min.**
- **Max span width 18 m**

All mounting and fixing work is done from above

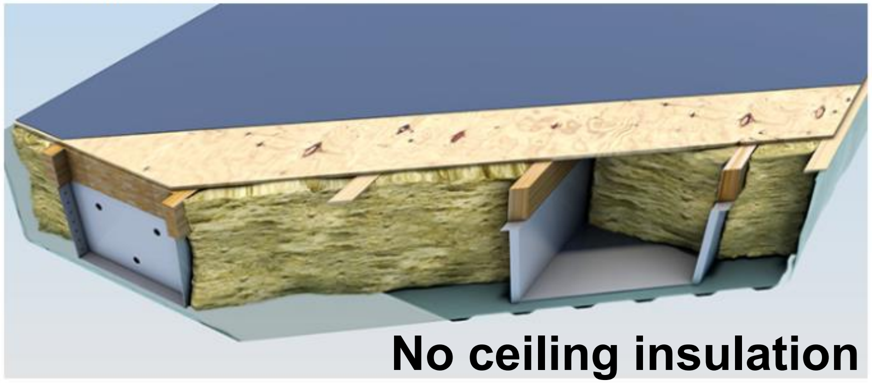
Cutaway illustration of Lett-Tak roof panel

- Composite-element, SINTEF TG-2215, ETA under preparation
- Roof panel width 2,4 m and max length 18 m
- 2 steel profiles, height from 130 up to 440 mm, thickness 1,0 to 2,0 mm
- Timber flanges 48x71, 48x96 or 48x121 mm glued or nailed to steel
- Finnish plywood,15 mm, 18 or 21 mm thickness glued to timber flanges

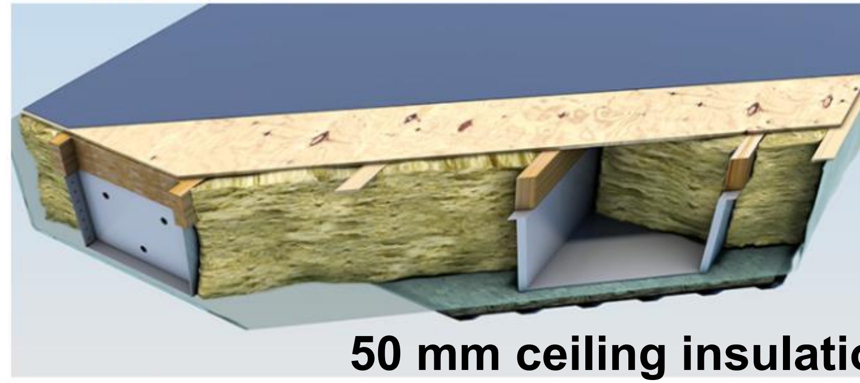


Fire resistance Lett-Tak roof panels

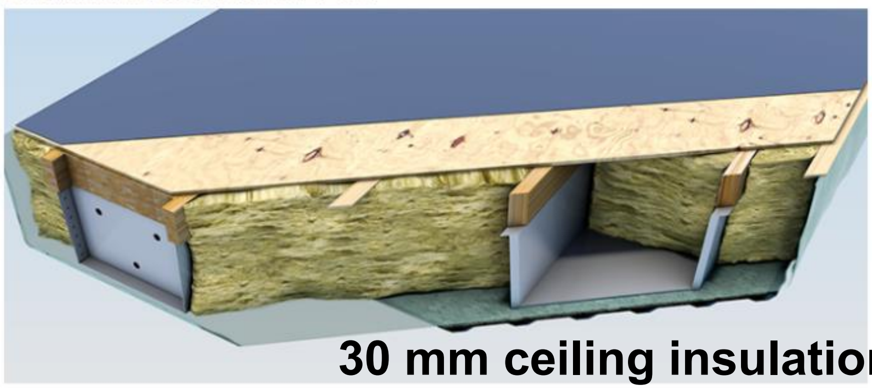
Brannmotstand REI-15



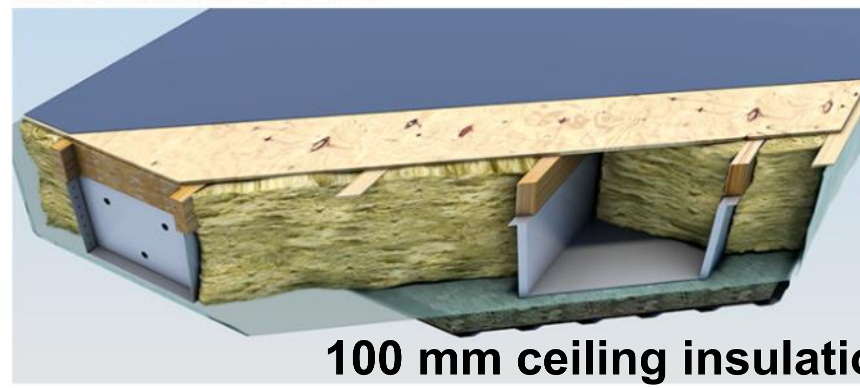
Brannmotstand REI-60



Brannmotstand REI-30



Brannmotstand REI-90



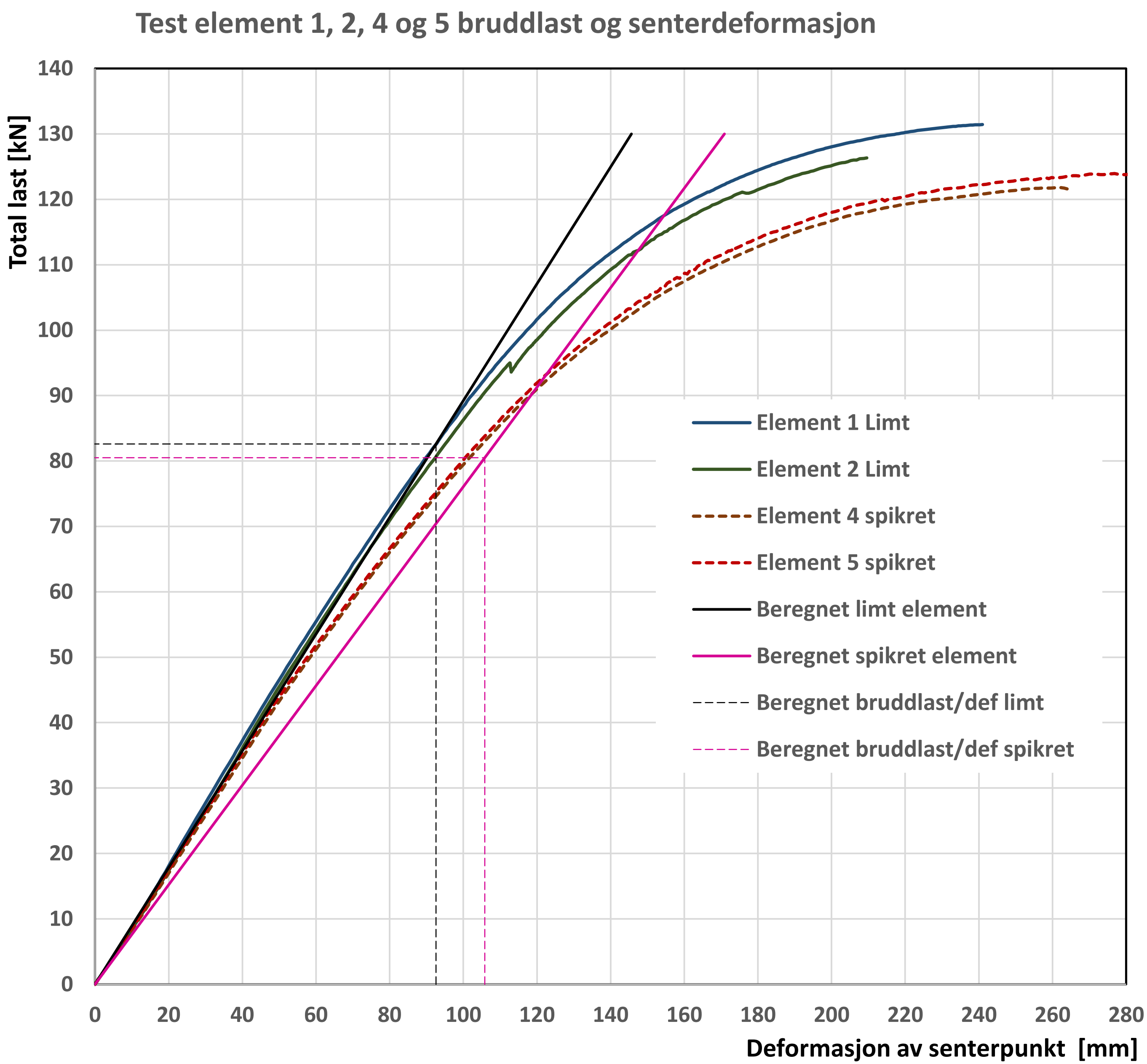
*) Rockwool Building 90, EN 13162 density min. 90 kg/m^3, λ_D = 0,034 W/mK

Fire resistance given for fire from underneath or from upperside, ref. ETA

Full scale test,10 m Lett-Tak roof panels at the Norwegian Building Research Institute for European Techncal Approval (ETA) 2015

From the full scale test of four Lett-Tak roof panels

Full scale test 4 stk 10 m Lett-Tak panels 14.1.2015

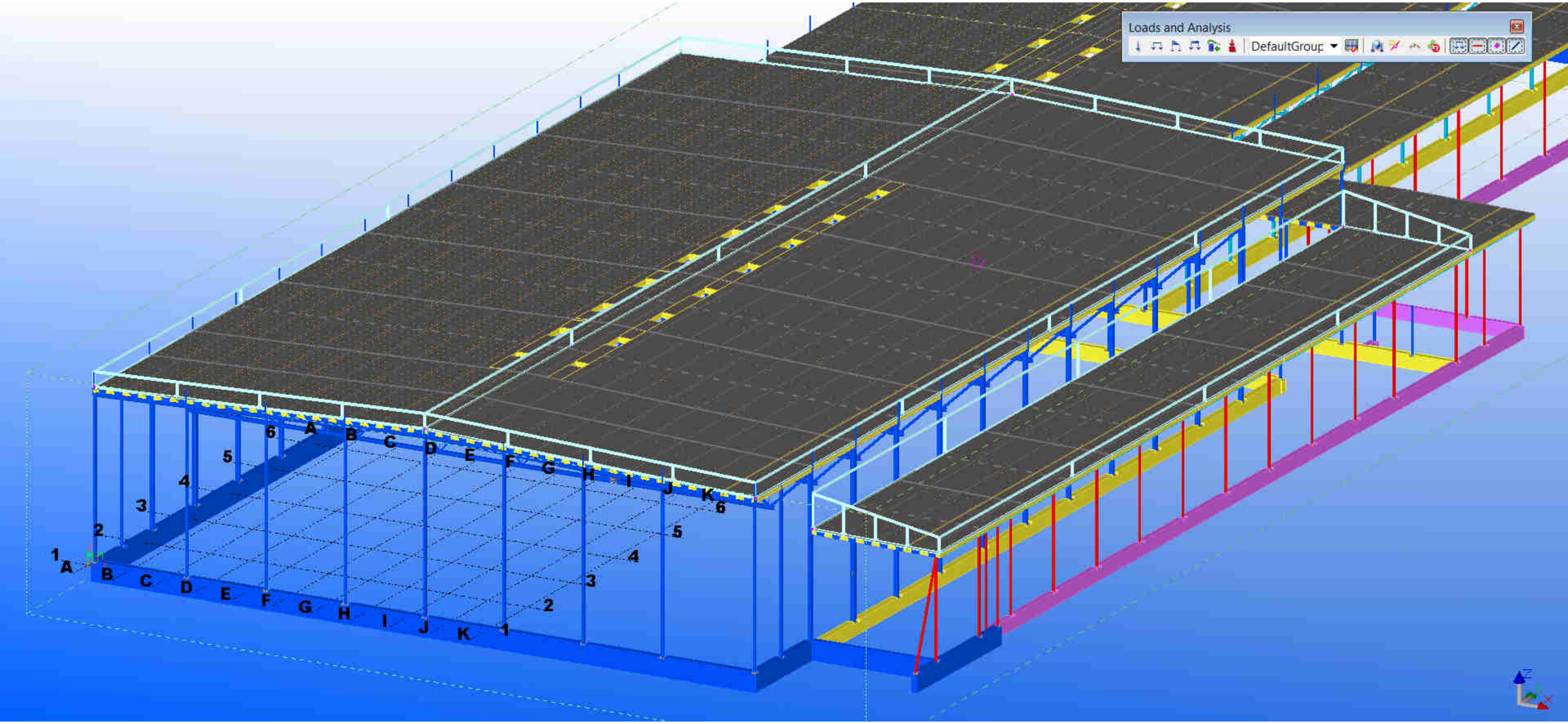


Screws in diaphragm structures

- Some screws shows brittle failures, before bending!
- Allways bend some screws by hand to confirm the ductility!
- Bending to 20-25° before failure is ok !

Design tools – Lett-Tak

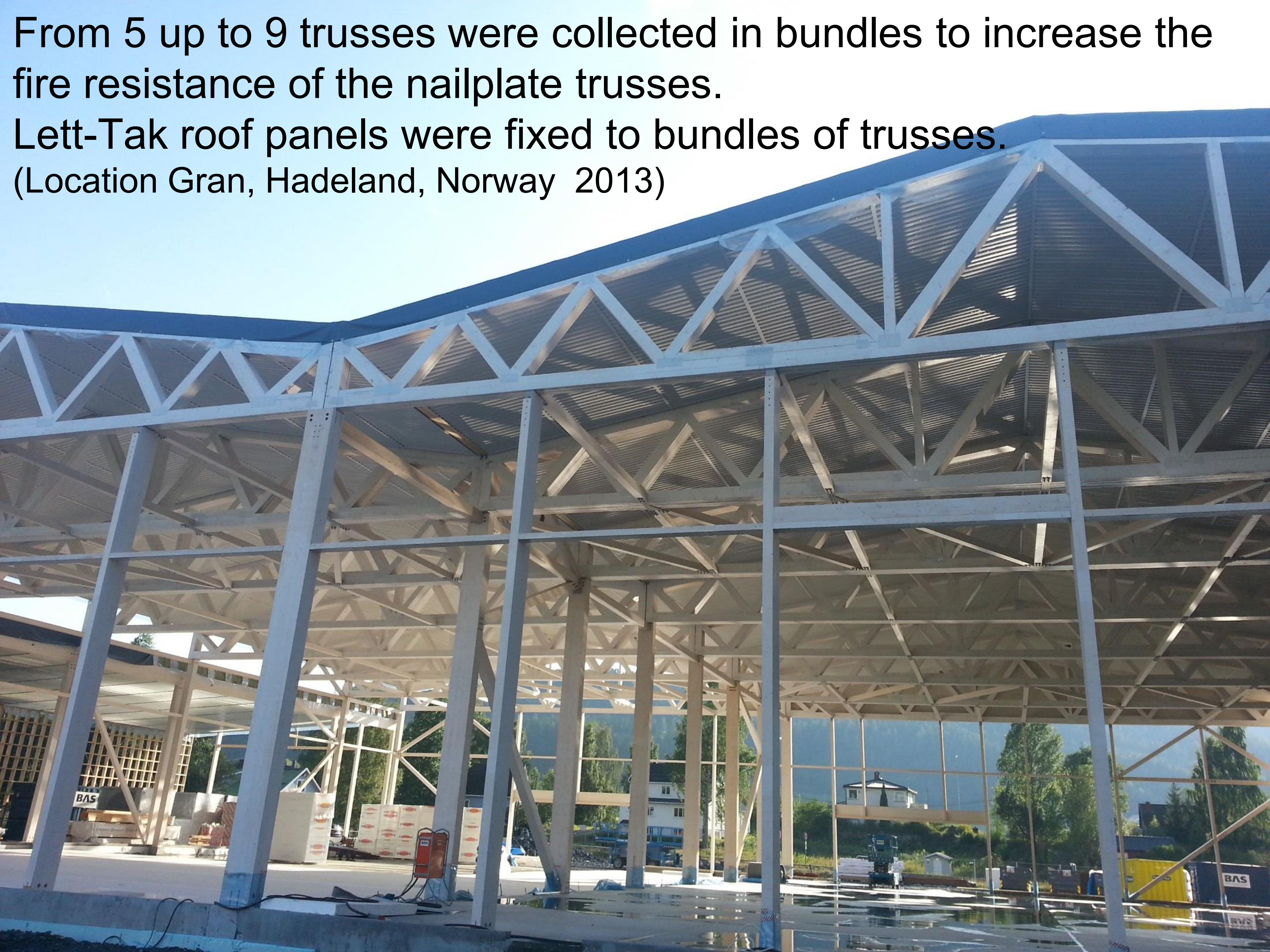
Tekla for BIM design of the projects with proprietary modul for Lett-Tak roof panels



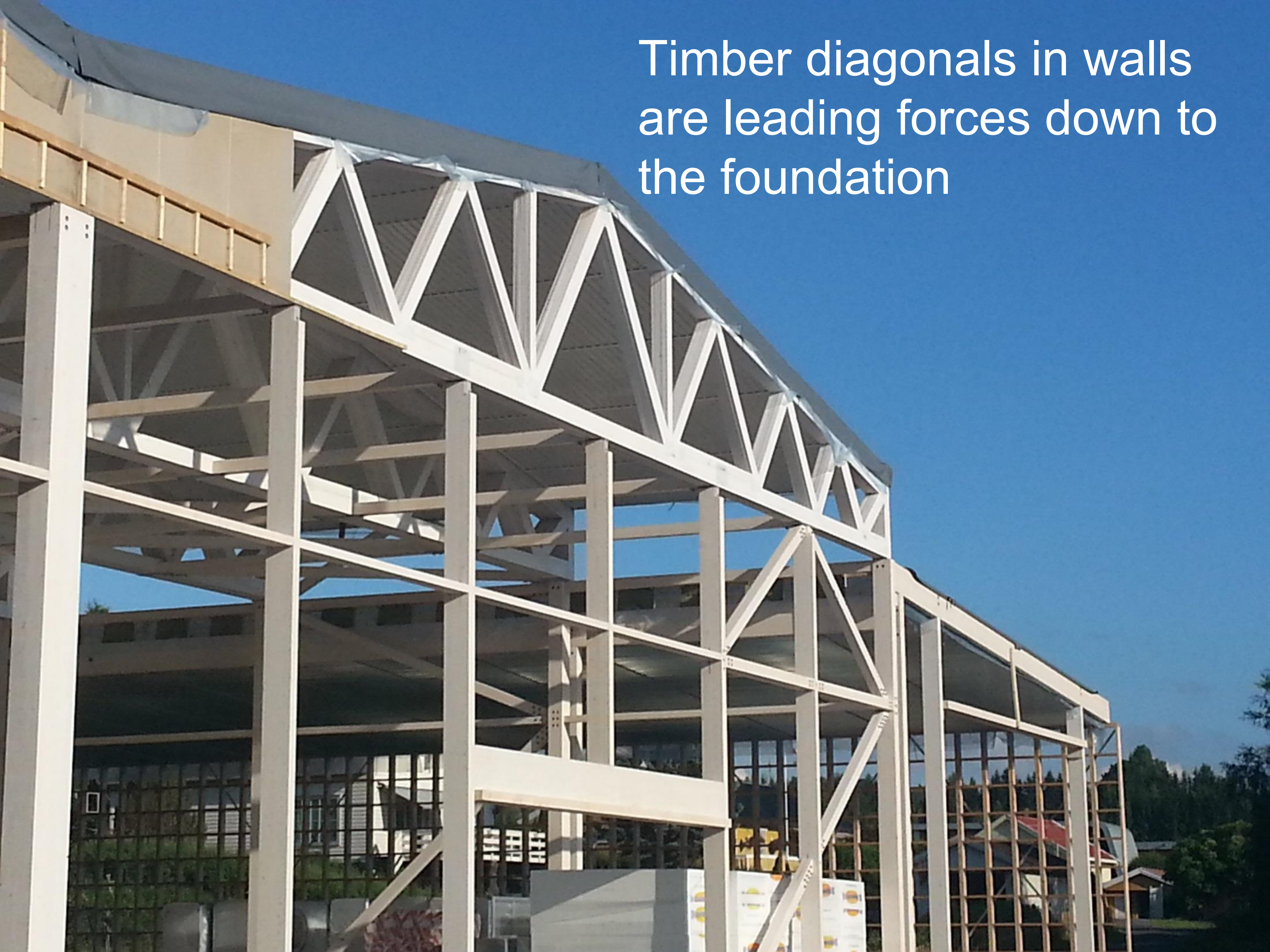
From 5 up to 9 trusses were collected in bundles to increase the fire resistance of the nailplate trusses.

Lett-Tak roof panels were fixed to bundles of trusses.

(Location Gran, Hadeland, Norway 2013)

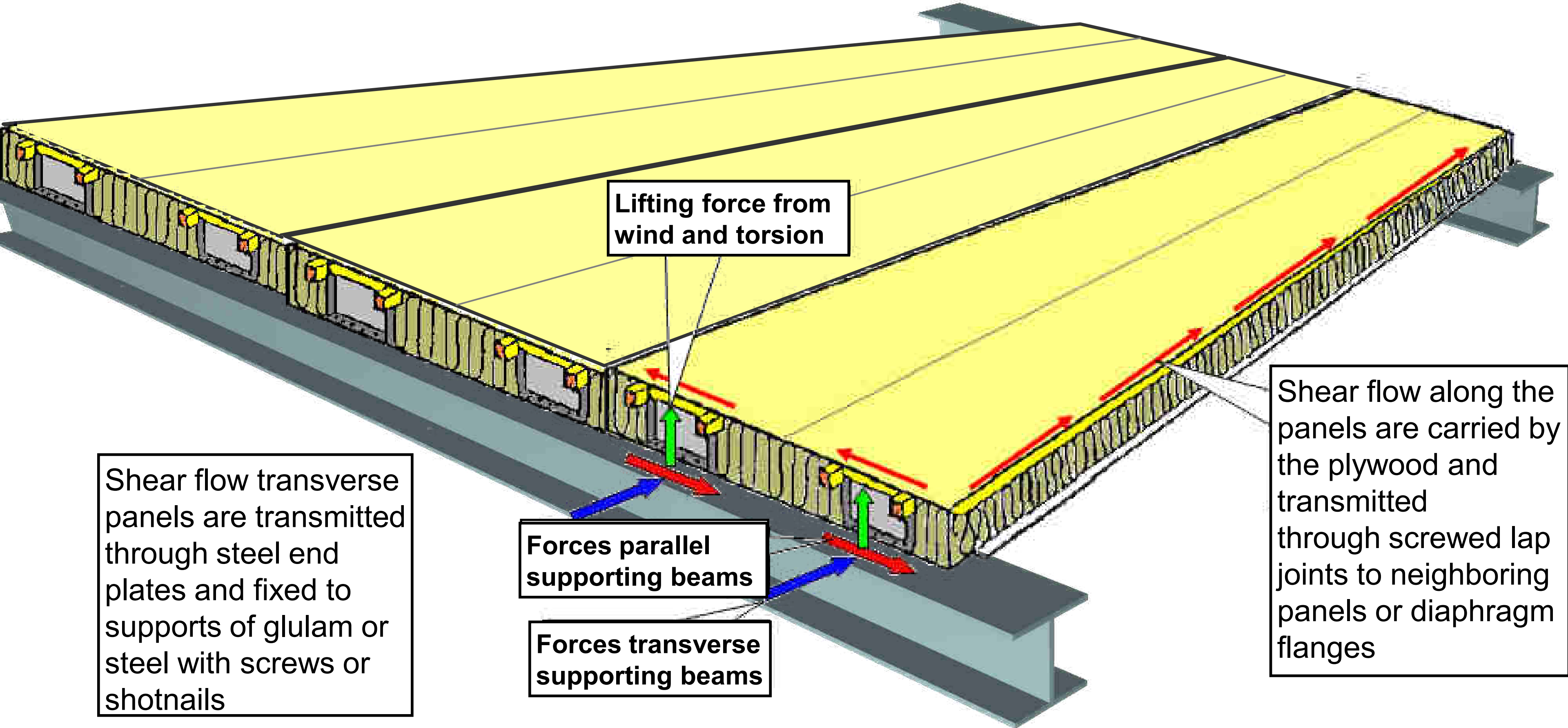



9 trusses collected
in one bundle
Lett-Tak
roof panels


Timber diagonals in walls
are leading forces down to
the foundation

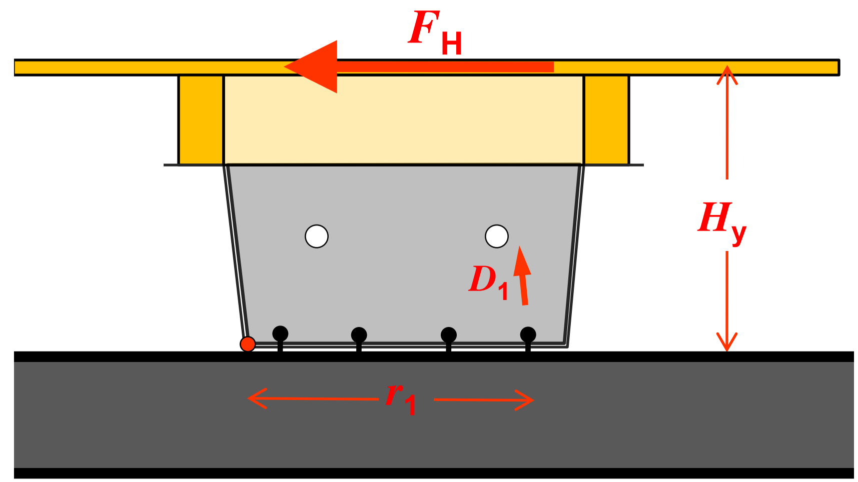
Norwegian project with bundled timber trusses in combination with Lett-Tak panels, 2013

The Lett-Tak system also gives the possibility for diaphragm action of the roof. The roof panels are taking care of the **shear flow** in the diaphragm. elementer

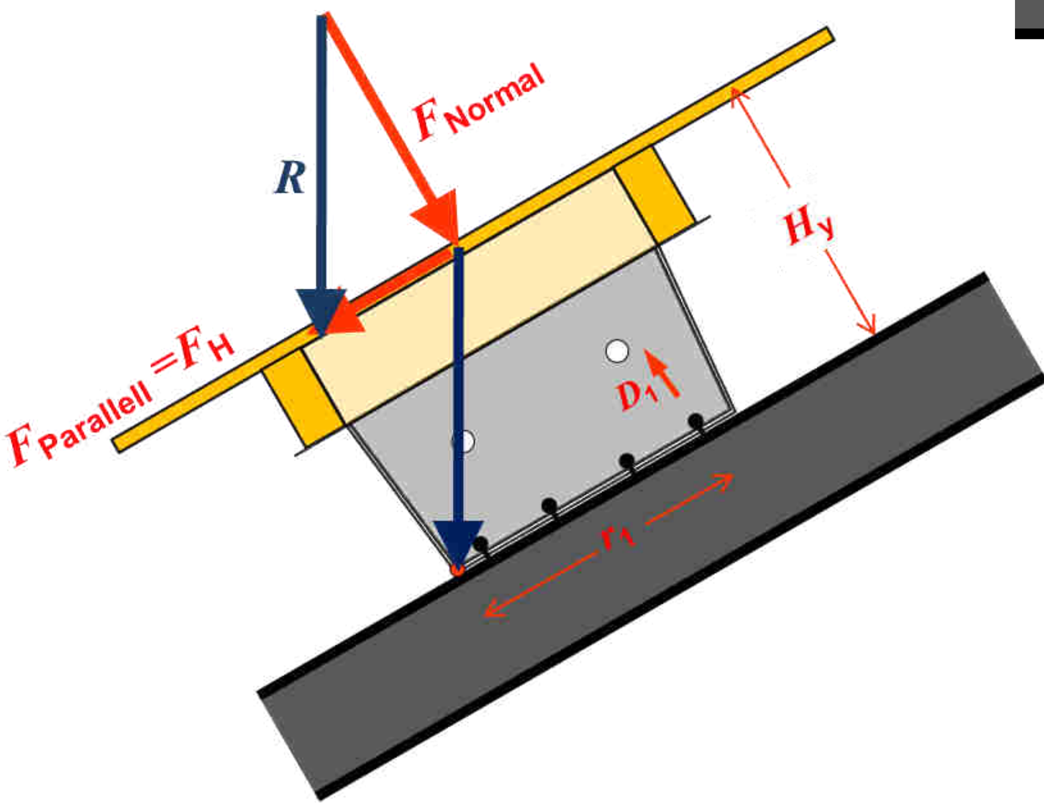


Axial forces in screws from shear flow F_H

$$D_1 = \frac{6 \cdot M \cdot (n-1)}{450 \cdot n \cdot (2n-1)} = \frac{F_H \cdot H_y \cdot (n-1)}{75 \cdot n \cdot (2n-1)}$$



D_1 – forces comes in addition to lifting forces from suction on the rooof and internal air pressure



Detail of connection to longitudinal wall

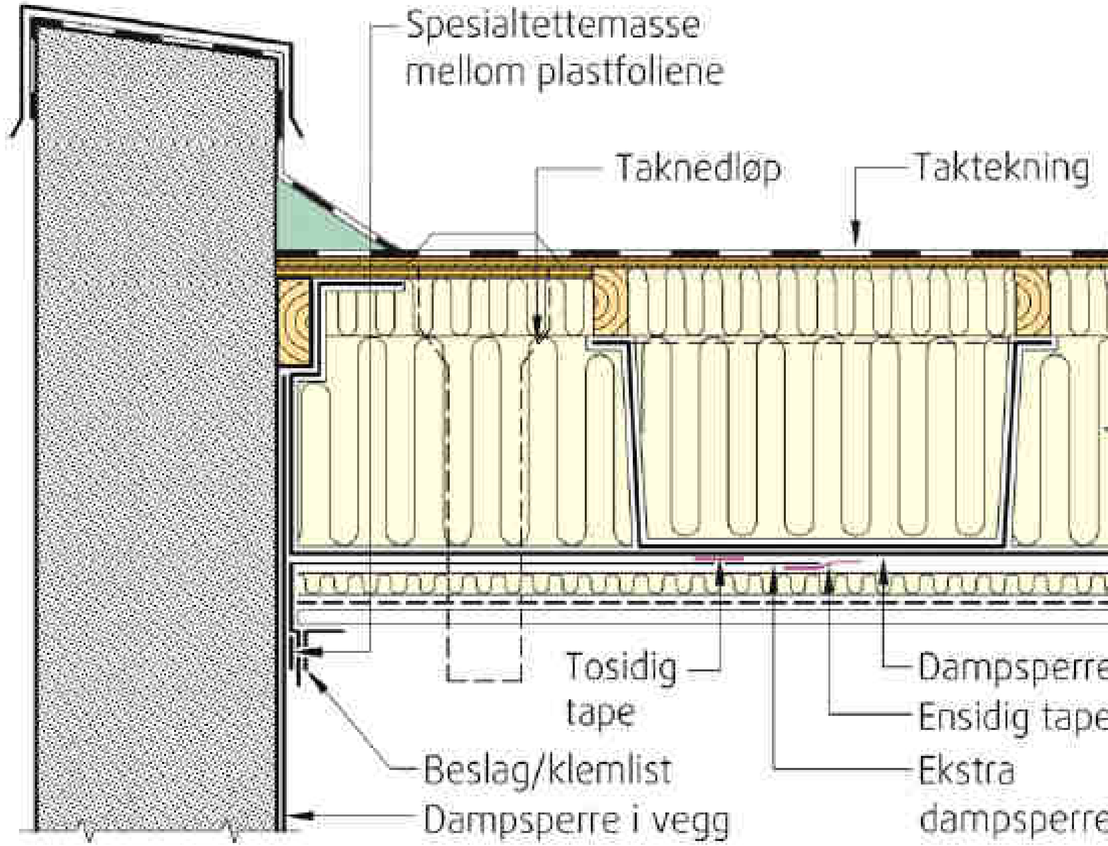


Fig. 3
Prinsipp for utførelse av tilslutning mot yttervegg. Det er forutsatt at veggen er reist før montasjen av takelementene.

Telenor Arena – Football and event hall

Covered and stabilized with Lett-Tak roof elements


Telenor Arena
Mounting the first
Lett-Tak roof
element
G1
FORNEBU ARENA

Telenor Arena – Football and event hall

Covered and stabilized with Lett-Tak roof elements

Telenor Arena – Football and event hall

Covered and stabilized with Lett-Tak roof elements

Swedbank Arena, Stockholm – Lett-Tak roof panels

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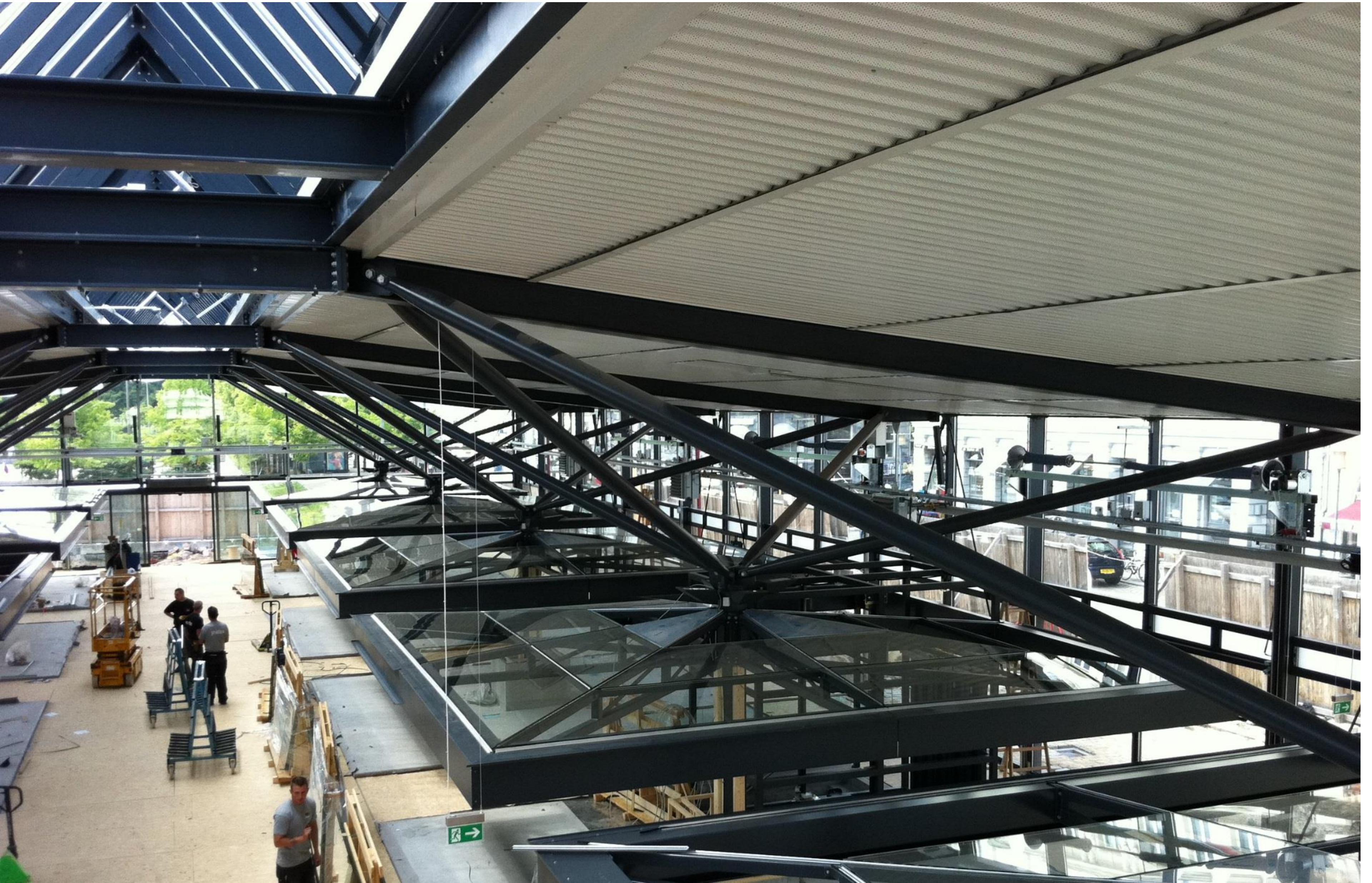
Torvehaller – in the centre of Copenhagen

A relatively soft (and weak) steel structure.
Stabilizing the whole buildings is an important function of the Lett-Tak roof panels in this project.

Torvehaller – in the centre of Copenhagen



Gardermoen airport – Lett-tak roof panels all over

New inland terminal – Gardermoen airport 2014
Main structure of Glulam,
covered and stabilized with Lett-Tak roof panels

Gardermoen Pir North 2014

- The roof panels in some part of the roof had to be twisted (double curved shape)
  Picture from the factory, testing twisting of roof panels
- Even if the panel is soft in the transverse direction, twisting up to 10° of 9 m long roof panels could be a challenge. Some steel end plates had to be skewed!

Gardermoen airport – Pir North 2015