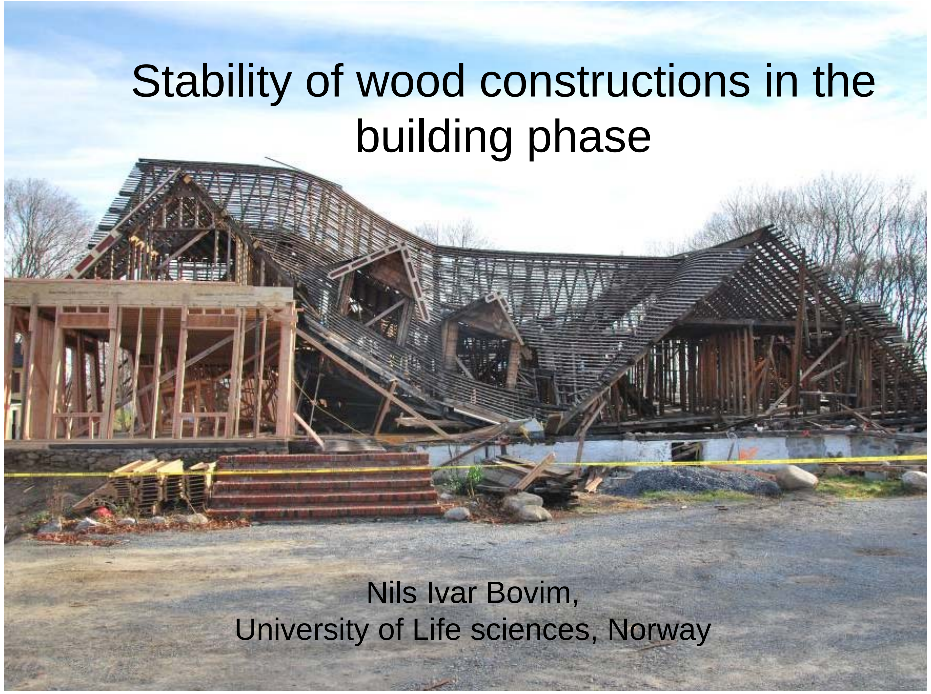


Stability of wood constructions in the building phase

Nils Ivar Bovim,
University of Life sciences, Norway

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.

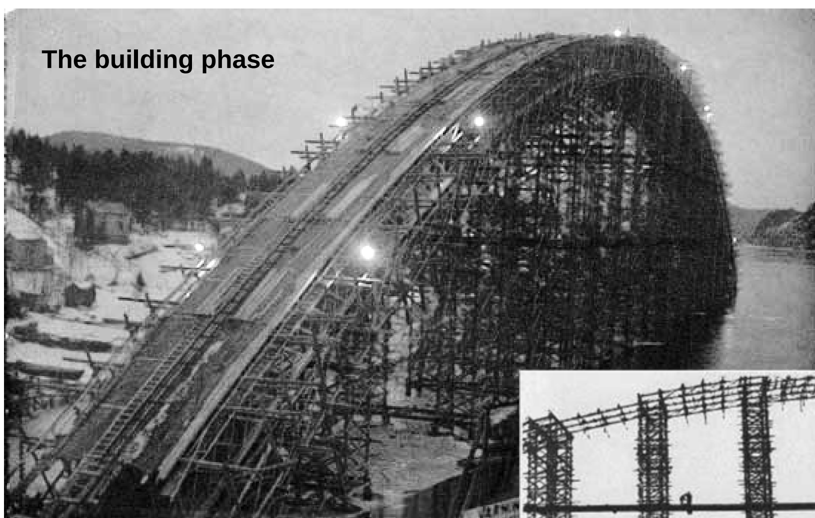
About **60% of the failures occur during the building phase**. Even if the problem is planning or design, the failure often occur during the building phase.

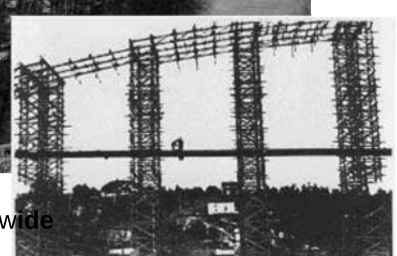
Failures where people were **killed or injured** is relatively worse, **65-70% occurs during the building phase**.

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

The building phase



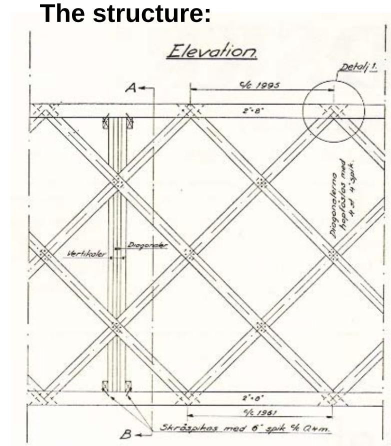


Formwork and scaffolding for Sandö Bridge, Sweden 1938-39. Arch span 264 m, 11,1 m wide

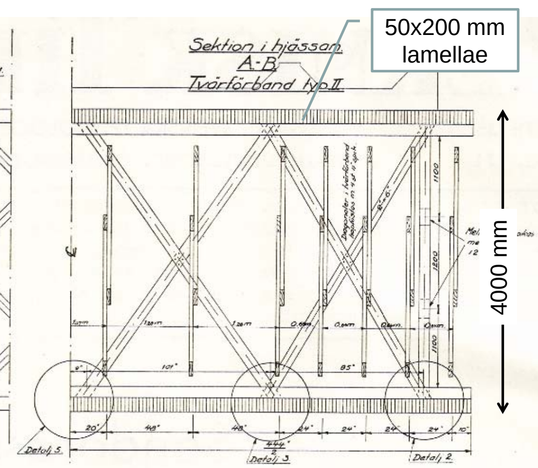
The highest scaffolding tower was 37 m.

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

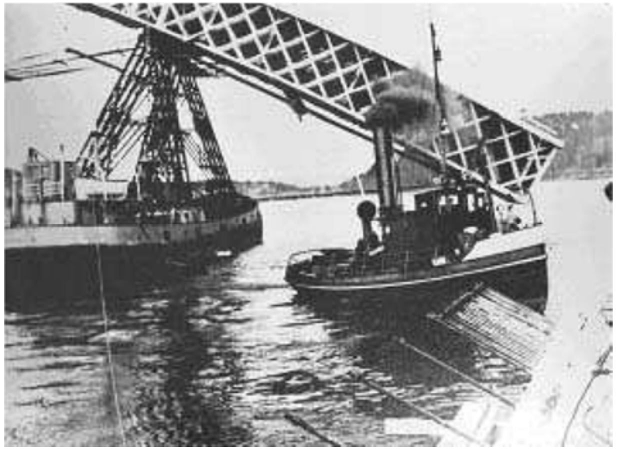
Upper and lower chord is parallel nailed (12″ nails) massiv wood structure with nailed diagonals in between. **Thickness of the chords is only 200 mm!**

Not only the most spectacular timber structure, probably also the most spectacular transportation operation

Formwork and scaffolding were buildt on the riverbank

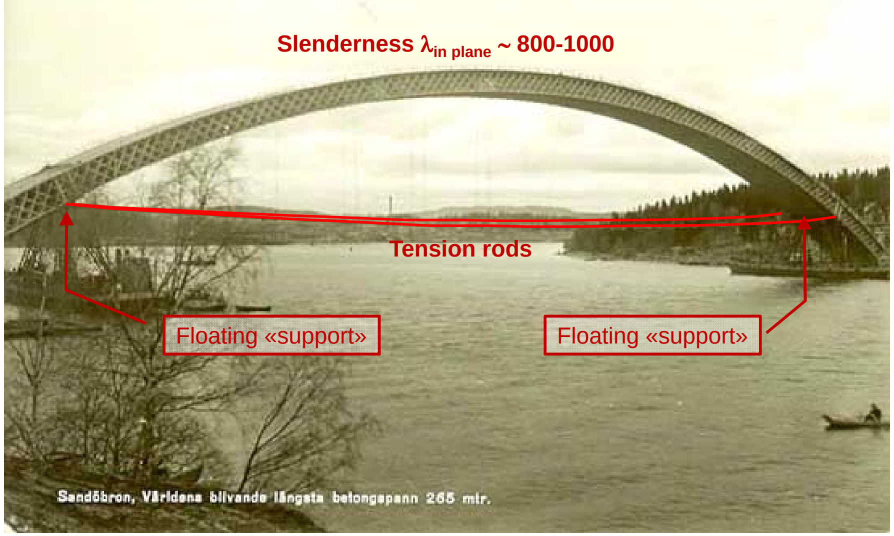
The scaffolding towers were removed an **the whole structure transported across the river with boats** at the 18th of May, 1939

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.

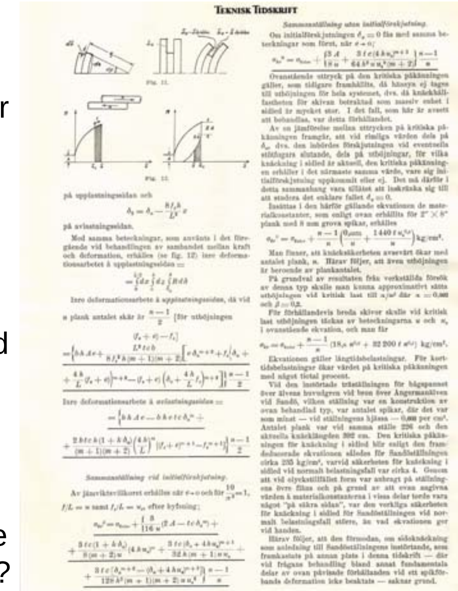
Witness descriptions indicated buckling in vertical direction (in plane) of the whole section as the failure mode.

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

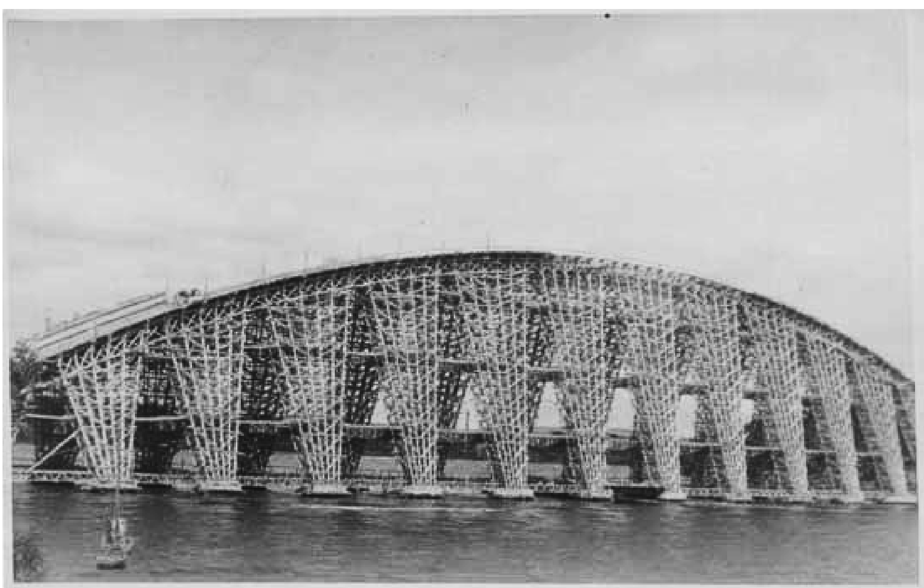
Later investigations have proposed lateral instability of the arch as responsible for the failure

Could we find the real problem today?

- Advanced analysis and testing of materials and joints formed the basis for the project
- After the collapse big effort were laid down searching for the causal factor
- The committee concluded that instability was the main problem, but no exact reason was found.
- Would someone start a new investigation with the new tools we have today?


Teknisk Tidskrift

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



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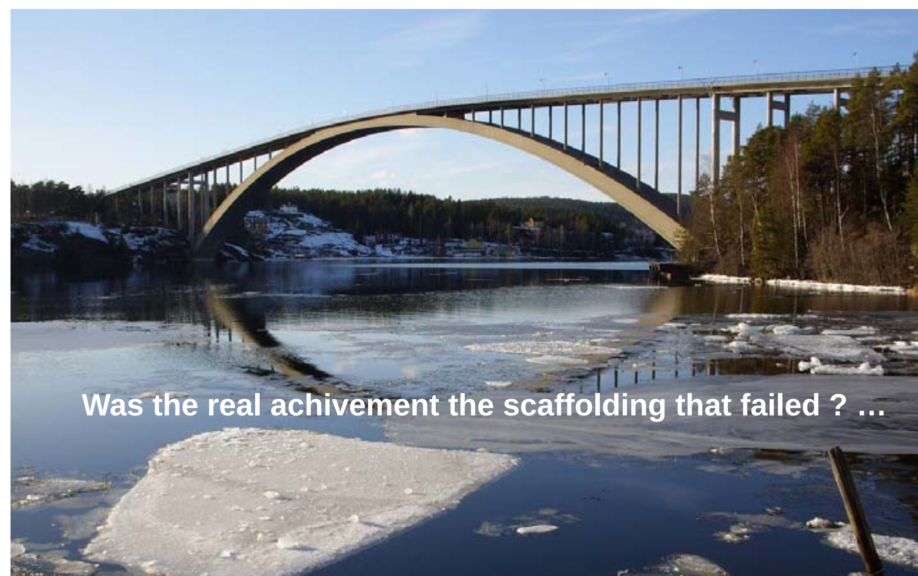


Instability of timber structures is a real problem – as for other materials

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

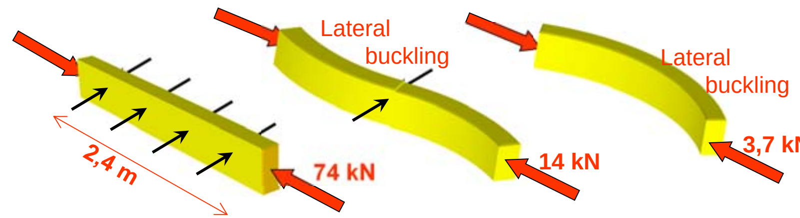
Failure mode	Percentage
Instability	30
Bending failure	15
Tension failure perpendicular to grain	11
Shear failure	9
Drying cracks	9
Excessive deflection	7
Tension failure	5
Corrosion of fasteners / decay	4
Withdrawal of fasteners	3
Compression	2
Other / unknown	21

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

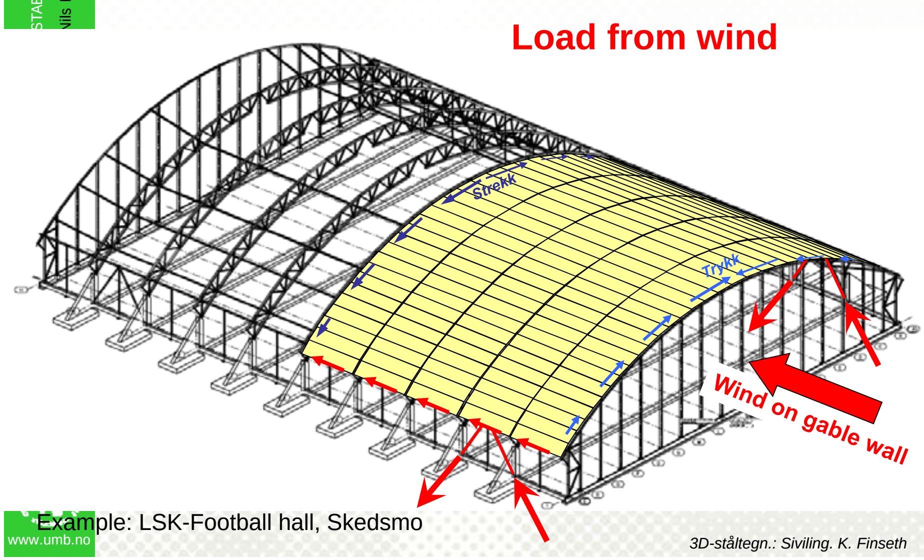
Effect av lateral bracing

Compression in a C24, 36 x 98 mm member 2,4 m long, :

- Complete lateral bracing
  Characteristic axial capacity $N_{c,k}$ = **74 kN**
- One stiffener in the middle - lateral slenderness λ = 115:
  $N_{c,k}$ = **14,1 kN**
- Unstiffened example - lateral slenderness λ = 230:
  $N_{c,k}$ = **3,7 kN**



Bracing diaphragm in arched building



Example: LSK-Football hall, Skedsmo

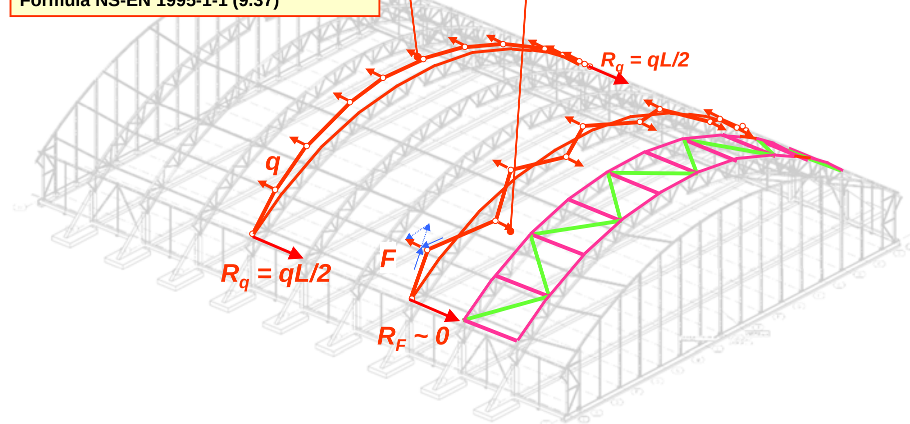
Loads on the bracing structure – simplified illustration

Unfavorable form of initial deflection regarding the stabilizing structure (trusses or disc)

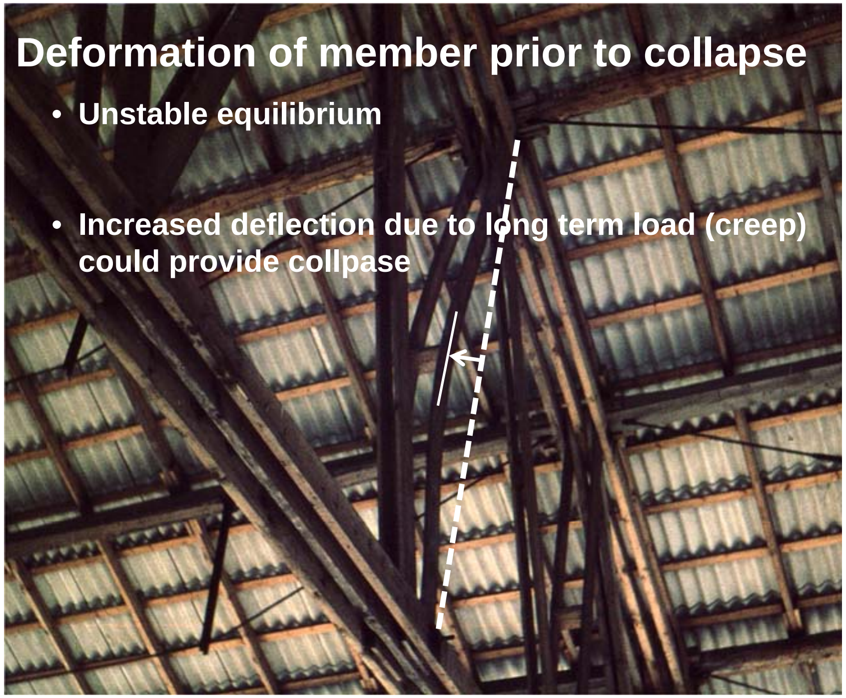
k_2 ~ 2 - 4% depending of fitting accuracy and the stiffness of bracing structure. Formula NS-EN 1995-1-1 (9.37)

Unfavorable form of initial deflection regarding the joints and load transfering structure

k_1 ~ 1 – 2% depending of fitting accuracy Formula NS-EN 1995-1-1 (9.35)



Eksempel: LSK-Storhall, Skedsmo



Deformation of member prior to collapse

- Unstable equilibrium
- Increased deflection due to long term load (creep) could provide collpase

Stability failure - lack of bracing

This photo was taken about 10 seconds before the 52’ scissor trusses collapsed. There was no wind load.
The top chord is buckling from a lack of proper top chord bracing

Failure of timber trusses in the building phase

Metal-plate-connected wood trusses are widely used

Flexible and unstable until set in place and adequately braced.

Truss-plate industry has developed handling and bracing recommendations, however, some installers ignore these guidelines

- Storage, Handling, and Erection Errors

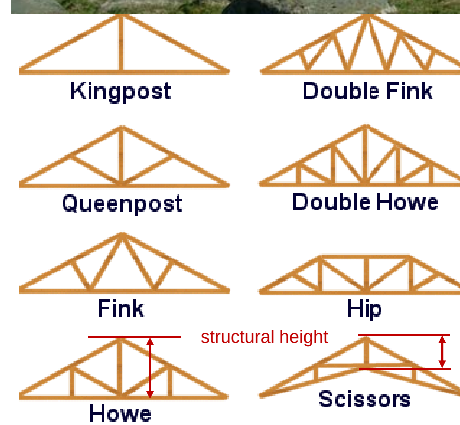
  Trusses should be stored in a dry, flat location, else:
  - Bending stresses in timber and joints could cause reduced strength,
  - Increased risk of instability failures due to higher initial deflection
  - Metal plates could "pop" or pull out at the joints

Ref.: *"Common Causes of Collapse of Metal-Plate-Connected Wood Roof Trusses"* , Harvey Kagan, Journal of Performance of Constructed Facilities, Vol. 7, No. 4, November 1993

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



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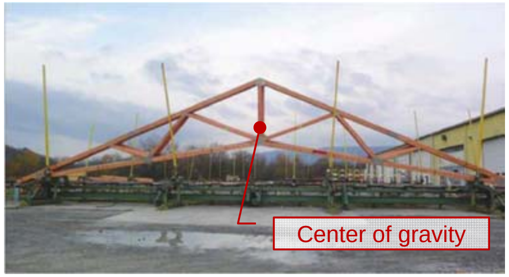

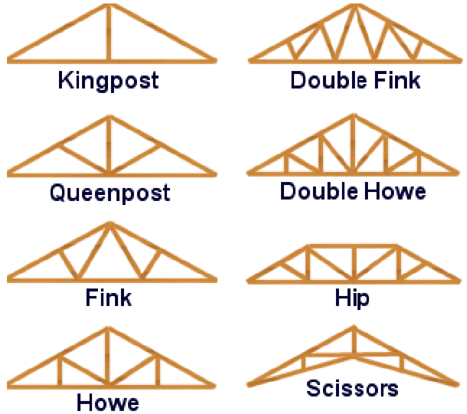

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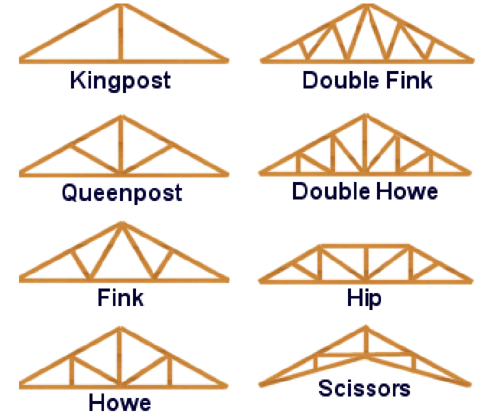
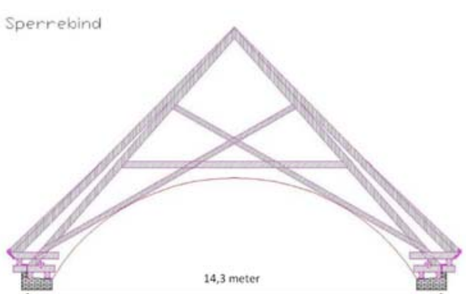
- horizontal forces in the supports tend to **push the supports outwards**



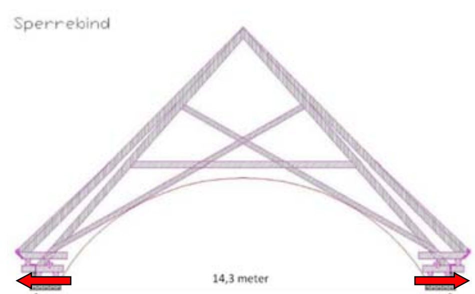
Example Oslo Cathedral (1694 -)

- 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)



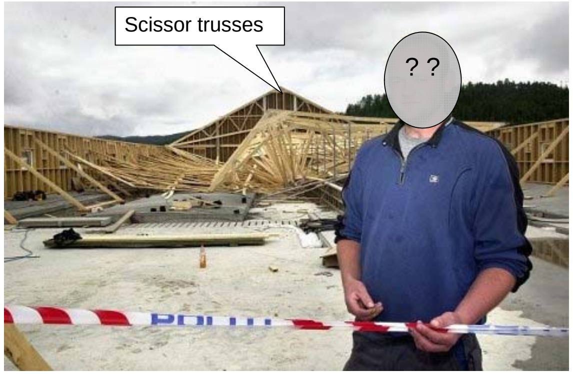
Lateral buckling of top chord

Deformations in roof due to lateral buckling of top chord of nail-plate roof trusses – as shown, even without snow load.

- Low-rise trusses with more than 20 m span result in high compression forces.
- **More than 30 super market buildings in several European countries had the same failure mode**, due to lack of purlin fixings and stabilizing diaphragm action

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

Lack of stability in the building phase is a system error – the trusses are not the main problem



Erection of an agricultural building in Norway– about 24 m wide:

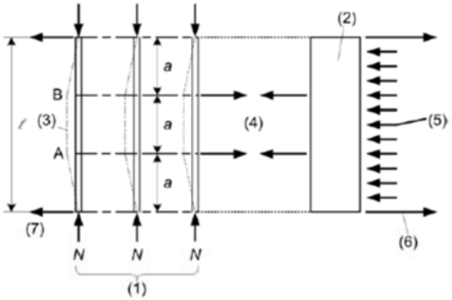
- *About half of the **scissor trusses** were installed when a truss 5 meters from the gable suddenly collapsed*
- *The rest followed **like dominoes**, falling one after another*
- *2 persons were working on the trusses, a **third person on the ground were injured**.*
- *There are found no problems with truss design or manufacturing*

Example of insufficient temporary bracing, scissor trusses enhances the stabilizing forces and effects of skewness.

Another example of short purlins, weak nailed joint on every truss and extra load from sheating packages

Stabilizing forces

- The stabilizing forces from each truss have to be transferred to a diaphragm or bracing structure
- The stabilizing forces are accumulated on their way to the bracing structure



Key:
(1) *n* members of truss system
(2) Bracing
(3) Deflection of truss system due to imperfections and second order effects
(4) Stabilizing forces
(5) External load on bracing
(6) Reaction forces of bracing due to external loads
(7) Reaction forces of truss system due to stabilizing forces

Ref. NS-EN 1995-1-1

Lack of stability in the construction phase

Failures and total collapse would be avoided if all stages of assembly are planned

What type of bracing system should be chosen?

Bracing of trusses

Temporary Bracing

Temporary bracing is required during erection to enable the truss assembly to:

- withstand the gravity forces of its own weight
- resist wind loads during construction
- support temporary construction dead loads such as the weight of sheathing and roofing materials
- keep the trusses plumb
- assure correct truss spacing

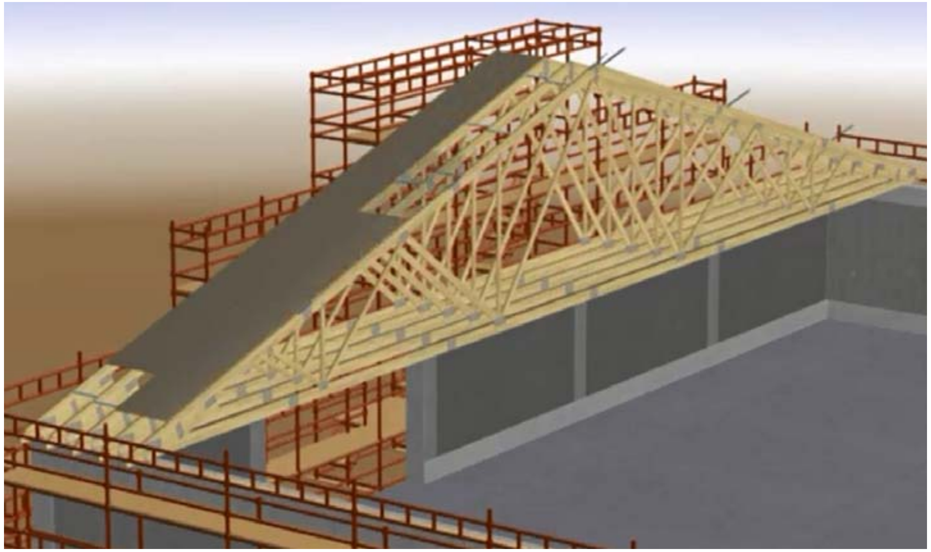
Permanent Bracing

Permanent bracing is required to ensure that the trusses are integrated into the overall building structure to:

- prevent buckling of web members loaded in compression
- share loads between adjacent trusses
- transfer lateral forces to diaphragms
- restrains overall lateral displacements

Ref. Canadian Wood Truss Association 2014

Guidelines from the Norwegian Truss industry



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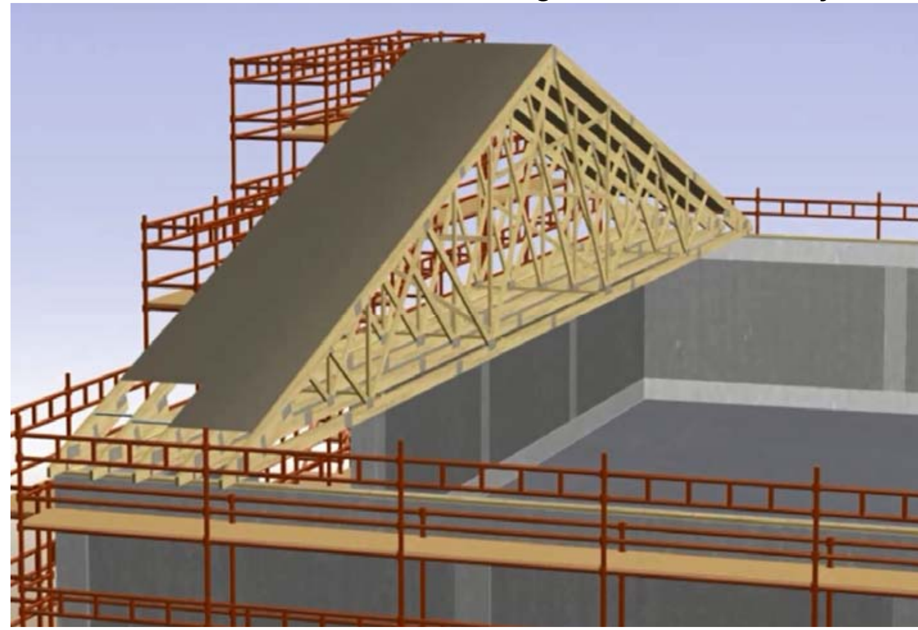

Total lack of bracing walls – house of cards

- is relatively stiffer

Complete instability failure in ground level from wind due to lack of racking resistance of wall cladding

Lack of overall stability for windload

Some concluding remarks …

- Failures (90%) are primarily caused by gross human errors. Increasing the formal safety level do not help!

Failures occur due to

- lack of knowledge in timber engineering (especially joints and stability)
- underestimated structural stability during the construction / building phase
- lack of identified body for the overall stability control (identify reponsibility)

Other remarks …

- Proper execution requires knowledge of stabilization of timber structures
- Lack of assembly plans and control of the complete stability of the structure is a real problem
- Manufacturer / reponsible consulting engineering should take responsibility for planning the assembly process and the complete safety of the building
- Lack of assembly plans and stability systems are an even bigger problem in small and medium sized buildings