# Robustness of large-span timber structures – Two examples

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Presentation based on

- Munch-Andersen & Dietsch in special issue of Structural Engineering

Failures reported in

- Hansson and Larsen: Recent failures in glulam structures and their causes. Eng. failure anaysis. 2005.
- Winter and Kreuzinger: The Bad Reichenhall ice-arena collapse and the necessary consequences on timber engineering. WCTE 2008.

# Siemens Arena, Denmark (2001)

Cycling arena with glulam trusses, span 73 m

Simply supported purlins, span 12 m

# Siemens Arena - failure

## 2 trusses failed (2600 m$^2$), no significant wind or snow

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# The reasons

Too high design strength

Reduced timber area at connection not accounted for

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=>

Load-bearing capacity only 25-30% of required

Failed due to $k_{mod}$-effect ("static fatigue")

# Siemens Arena - robustness

Strategy against progressive collapse:

- Trusses are key elements
- Purlins moderately fastened to trusses

Strategy worked! Only 2 of 12 trusses failed

Extend of collapse not disproportionate to the cause

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Alternative strategy:

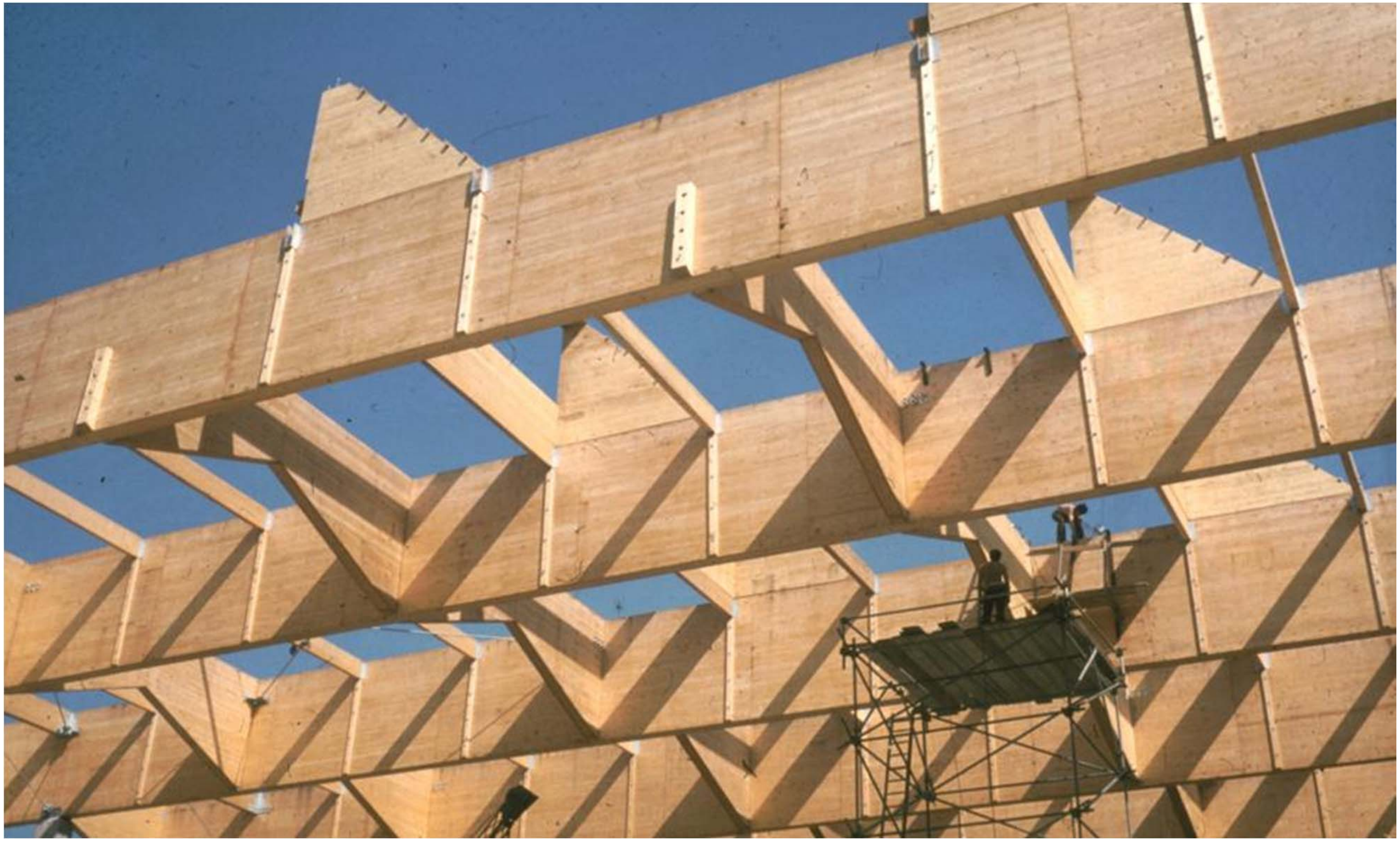
- Secure purlins so they can carry a failed truss

Successful only if the cause of failure is local and affects only one truss (overloading, leaking roof)

# Bad Reichenhall Arena, Germany (1972)

Ice-arena with 2.9 m high box-girders, span 48 m

Finger joints in girders per 16 m, K-shaped bracing



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# Bad Reichenhall Arena - failure

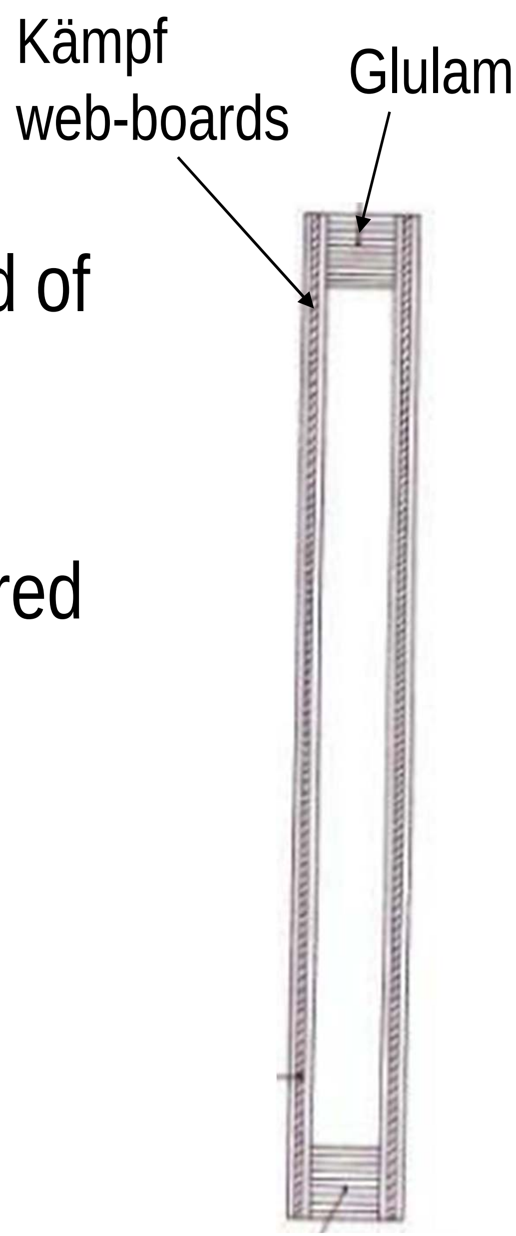
## Entire roof collapsed, snow below characteristic value

# The reasons 1

Design:

1. Bending strength of glulam used in stead of tensile and compressive strength
2. No reduction for finger joints in girder

1+2: Load-bearing capacity ~ 75% of required



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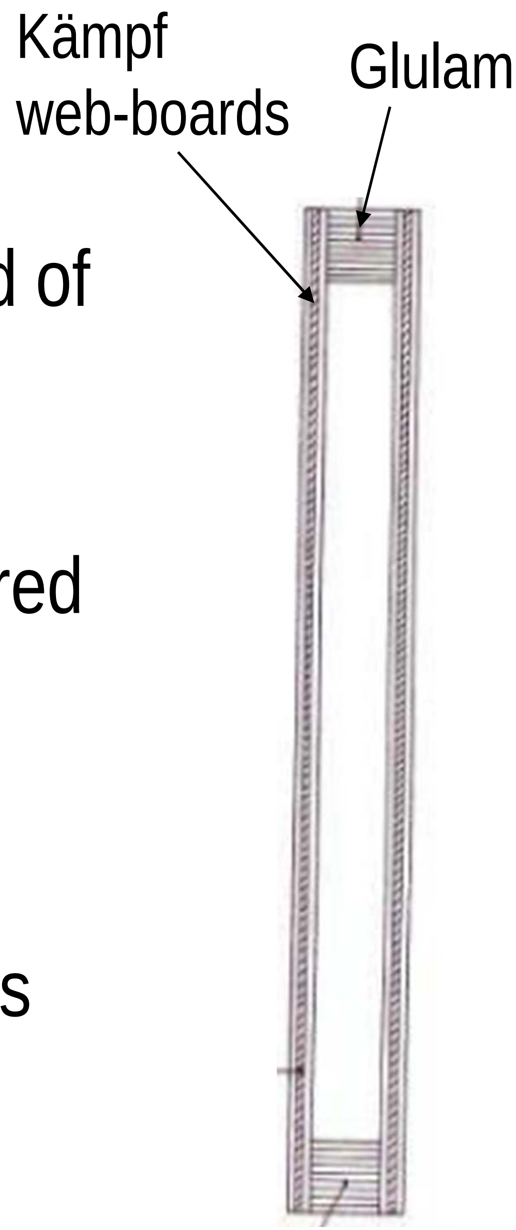
3. Kämpf web-boards (~Cross Laminated Timber) only approved for height 1.2 m and provided resorcinol glue is used
4. Urea-formaldehyde glue used, which was and are not allowed in humid conditions

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# The reasons 2

Construction and maintenance:

1. Bad quality of glue-line
2. Water penetration due to leaking roof
3. New knowledge: Condensation on lower side of girders due to radiation from the ice

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Collapse caused by degradation of glued connections over time combined with design errors

# Bad Reichenhall Arena - robustness

Robustness not considered during design

Highly statically indeterminate and redundant structure
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- Some girders may have lost their strength long ago
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- The redistribution is not observed because the bracing is very stiff

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Redundant systems must be designed to show when they redistribute load

# Discussion

*Siemens*

- Statically determinate
- Large systematic errors from beginning

*Bad Reichenhall*

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- Redistribution compensates for degradation
- Degradation in a single point might never had revealed

# Discussion

*Siemens*

- Statically determinate
- Large systematic errors from beginning
- Nowhere to redistribute load to
- Redundancy would have caused progressive collapse
- A purely local error would involve nearly 2000 $m^2$ of roof – perhaps not proportional to the cause

*Bad Reichenhall*

- Statically indeterminate
- Some systematic errors + random degradation
- Redistribution compensates for degradation
- Degradation in a single point might never had revealed
- Reduced safety not shown so complete collapse for minor incident possible

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# Conclusions

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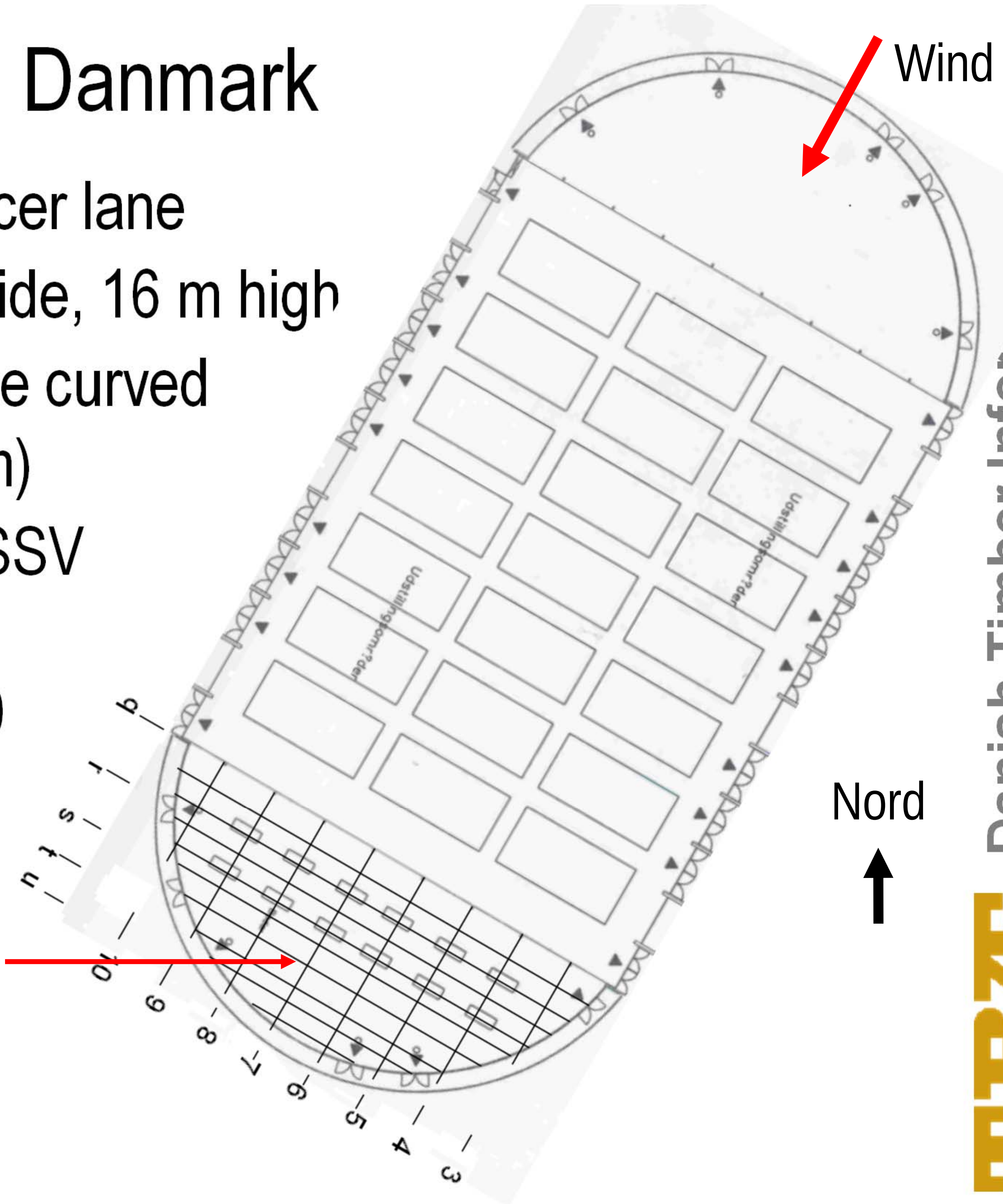
- Compartmentalisation can prevent progressive collapse
- Redundancy within a compartment can minimize risk from random errors – redistribution must show
- Eurocode focus on redundancy for ensuring robustness – not applicable to large-span roofs

# Recent failure in Danmark

- Sports hall with soccer lane
- 177 m long, 78 m wide, 16 m high
- Apsis halls with large curved glulam beams (32 m)
- Apsis hall towards SSV collapsed on Christmas eve 2010

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# Apsis hall

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# Apsis hall after collapse

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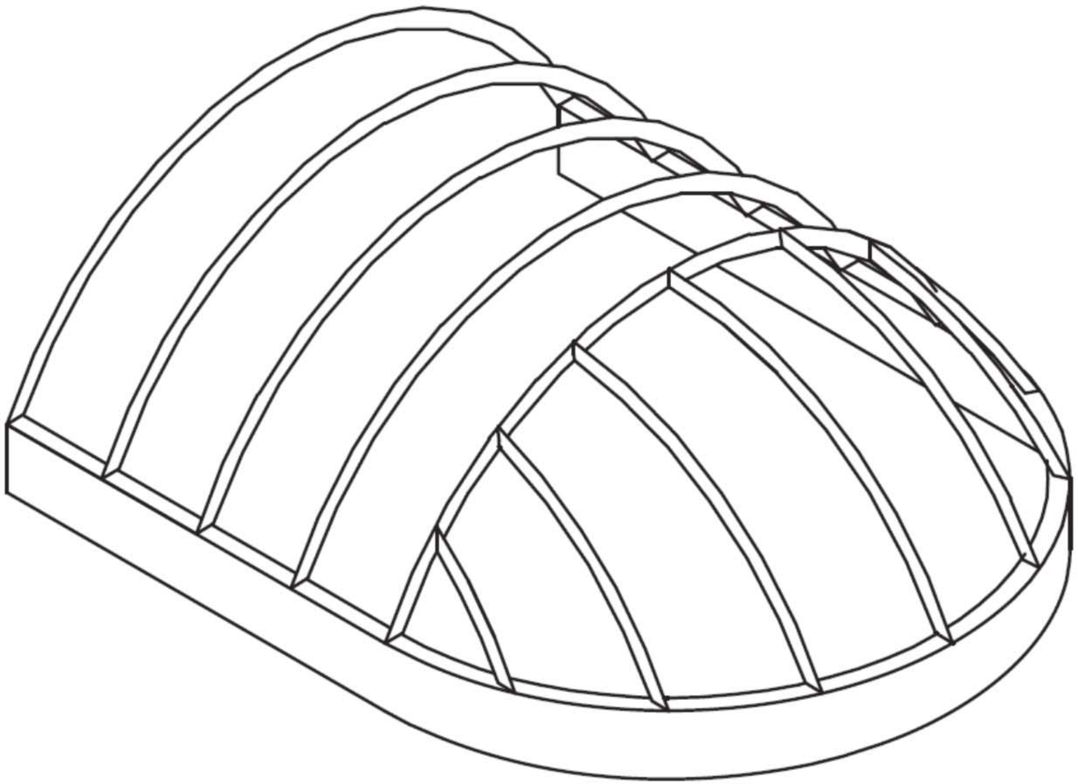
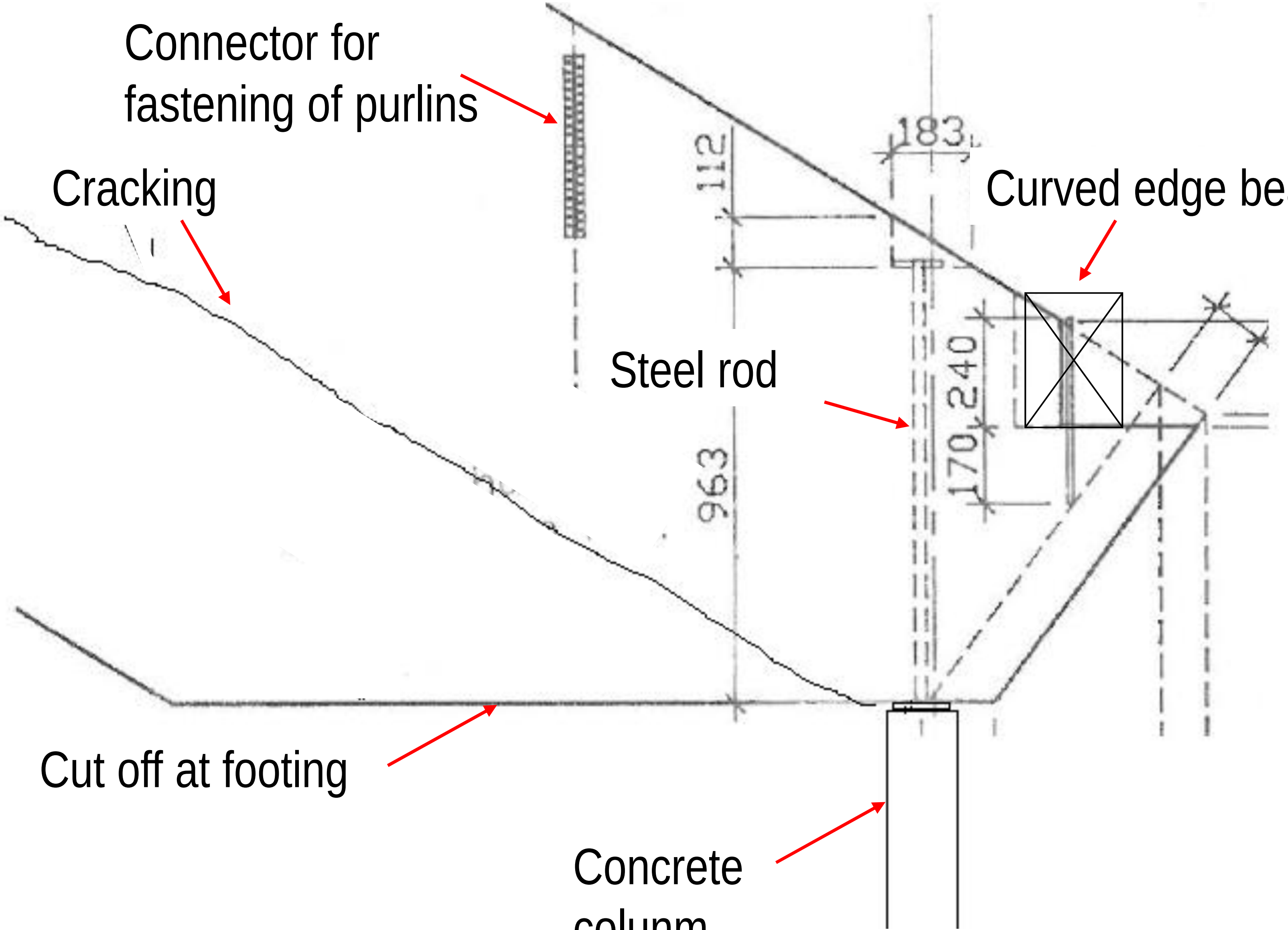
# Causes

- Only designed for shape factor 0,8 (as normal roofs)
- Curved beams designed as normal beams
- Non-considered shell effect due to edge beam



# Curved beam support at facade



# Curved edge beam serves as tension cord

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# Fixing of edge beam to main structure

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# Summary

- The edge beam is a secondary structure not designed as tension cord
- Tension in edge beam converts the roof to a shell
- Failure of the edge beams fasteningincreases suddenly the actions on the main beams =>

  1 cracks devellops

  2 the curved main beams are opened a bit and moves perpendicular to the curved facade which causes torsion

So: secondary load-carrying capacity might be dangerous!

(no warning, impact load on main structure when it fails)

Thank you - Questions?

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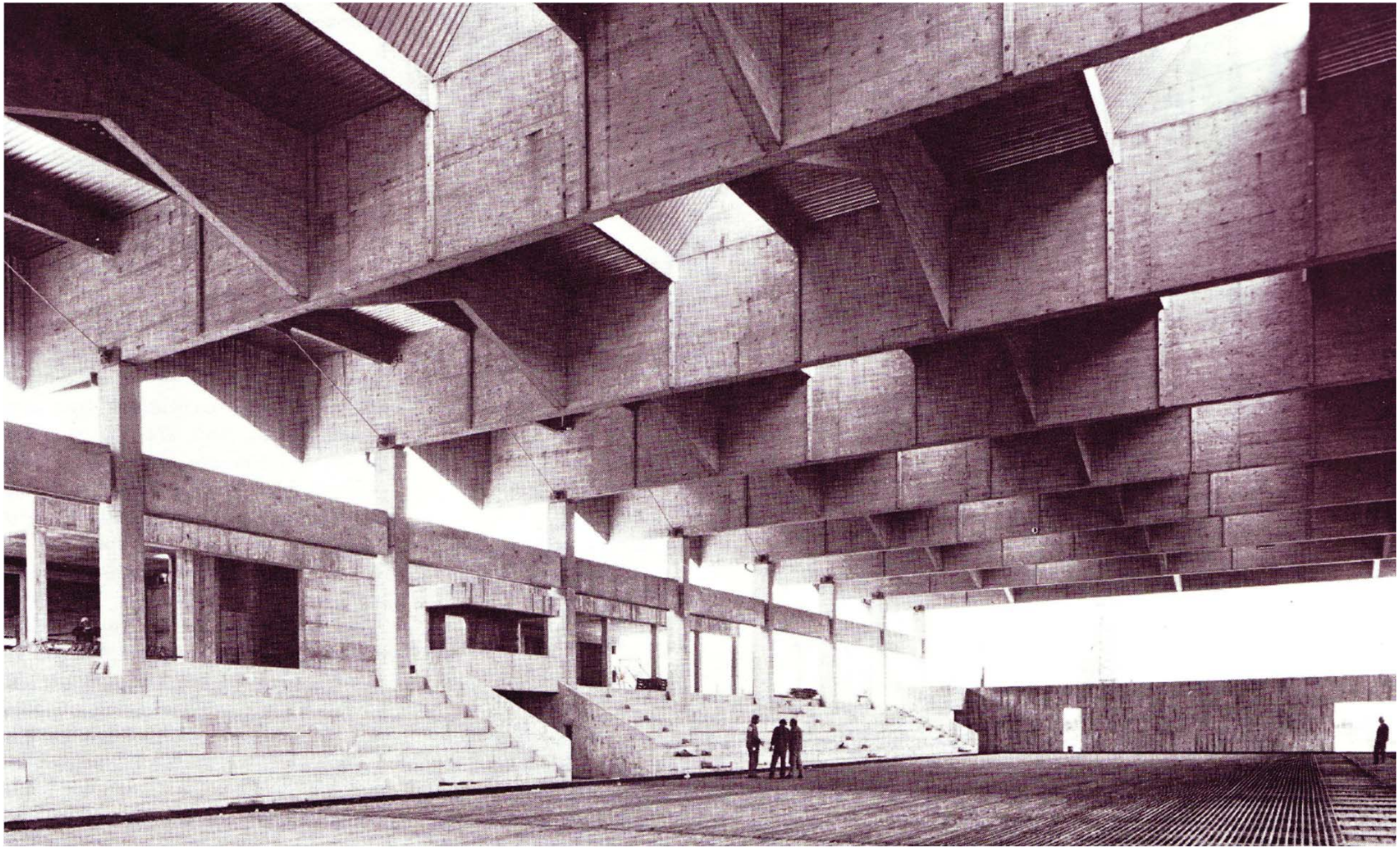

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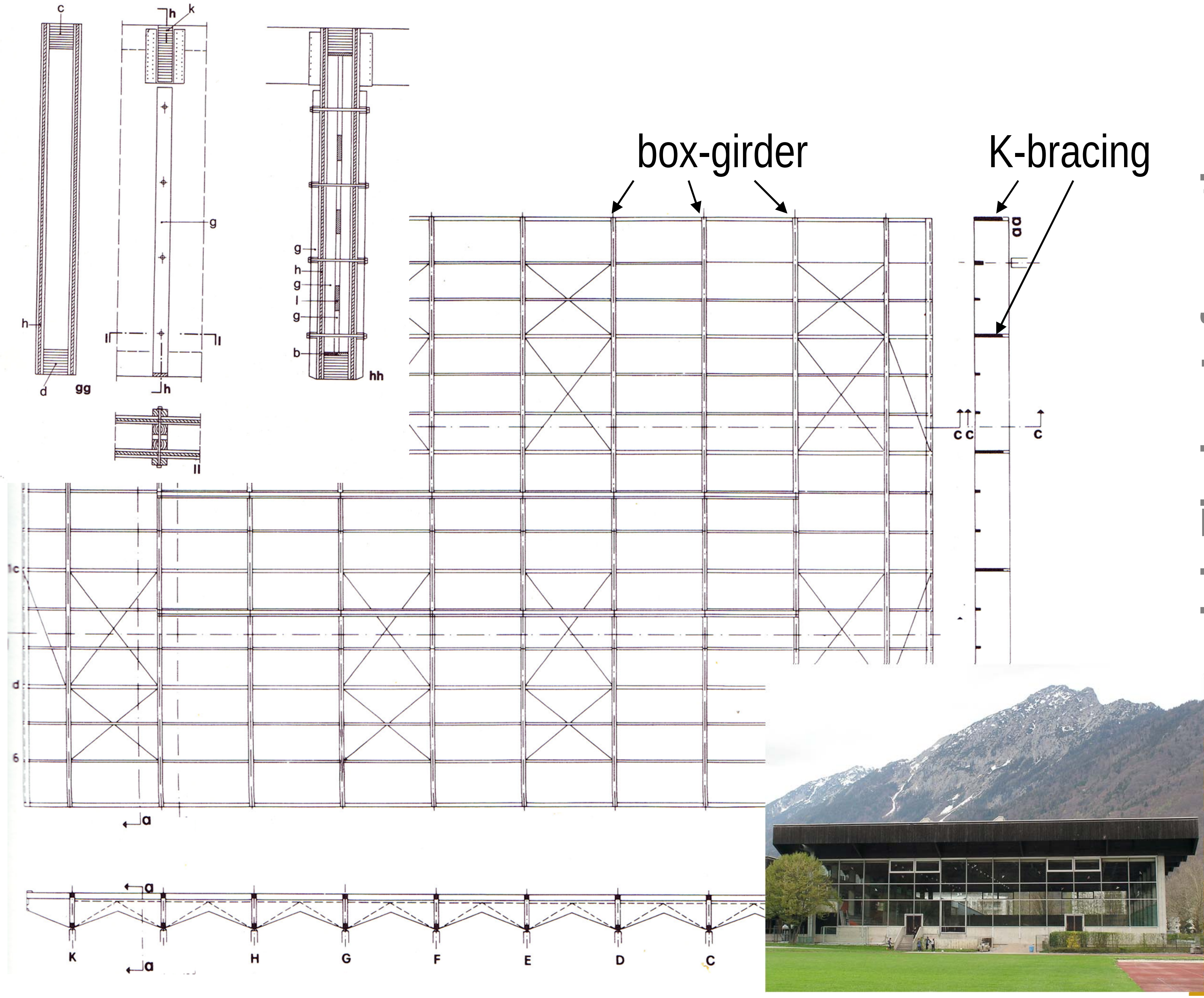


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