Design of safe timber structures – how can we learn from structural failures?

Collapses in Sweden 2010

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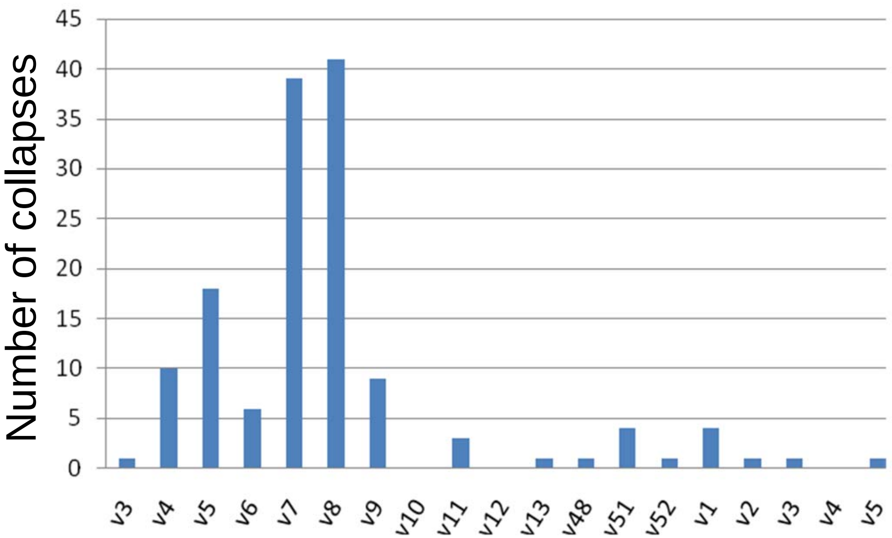
Collapses in Sweden winter 2009/2010/2011

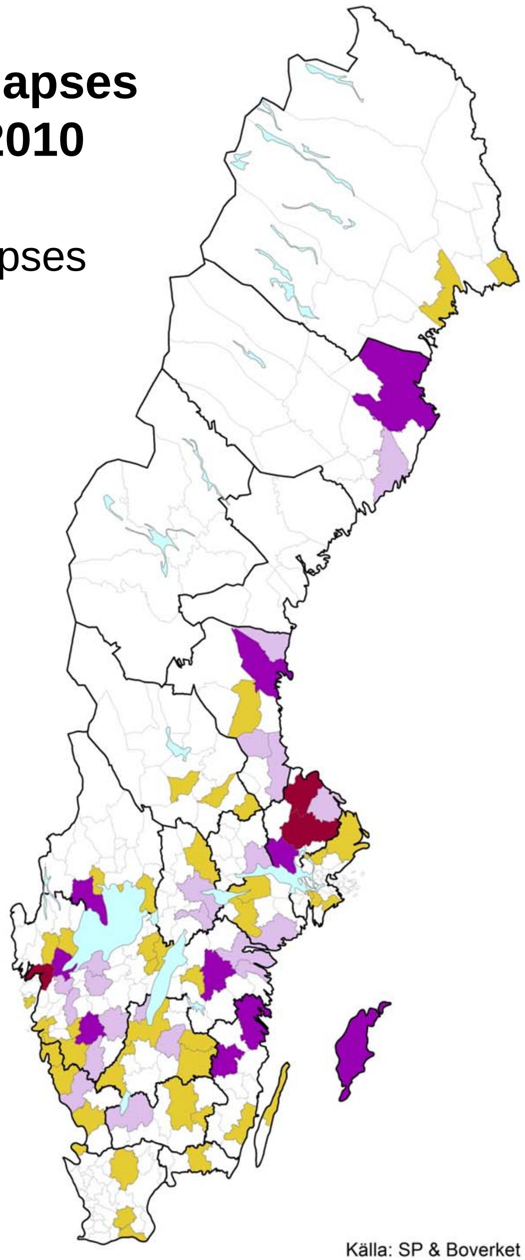
- Snowy winter
- Many collapses during january/february 2010



Reported collapses Winter 2009/2010

Number of collapses per municipality

- 7-9
- 4-6
- 2-3
- 1



Collapses in Sweden during winter 2009/2010/2011

- Swedish government assigned Boverket (National Board of Housing, Building and Planning) to investigate the reasons for collapses
- Investigation was carried out by SP (Technical Research Institute of Sweden)
- Parallel projects with common focus with other financers
  - SLU (Swedish Agricultural University)
  - Skanska Teknik
- The three projects were coordinated and resulted in a common report, which will be published 2011-05-31 (reported to the government): Roof collapses winter 2009/2010 and 2010/2011 – reasons and proposals for actions

Report: Roof collapses winter 2009/2010 and 2010/2011 – reasons and proposals for actions; Carl-Johan Johansson, Camilla Lidgren, Christer Nilsson, Roberto Crocetti

Contents

Collapses in Sweden
winter 2009/2010/2011

- About 3500 damages reported to insurance companies
- 180 collapses in SP database (167 + 13)
- 37 cases investigated thoroughly

Type of building and structural material

Type of building	number	%
Sportinghalls, icerinks, eventhalls	14	8
Riding halls	6	4
Schools	2	1
Shops	5	3
Industrial buildings	4	2
Storage buildings	22	13
Agricultural buildings	65	38
Other	52	31
Sum	170	100

18%
Public buildings

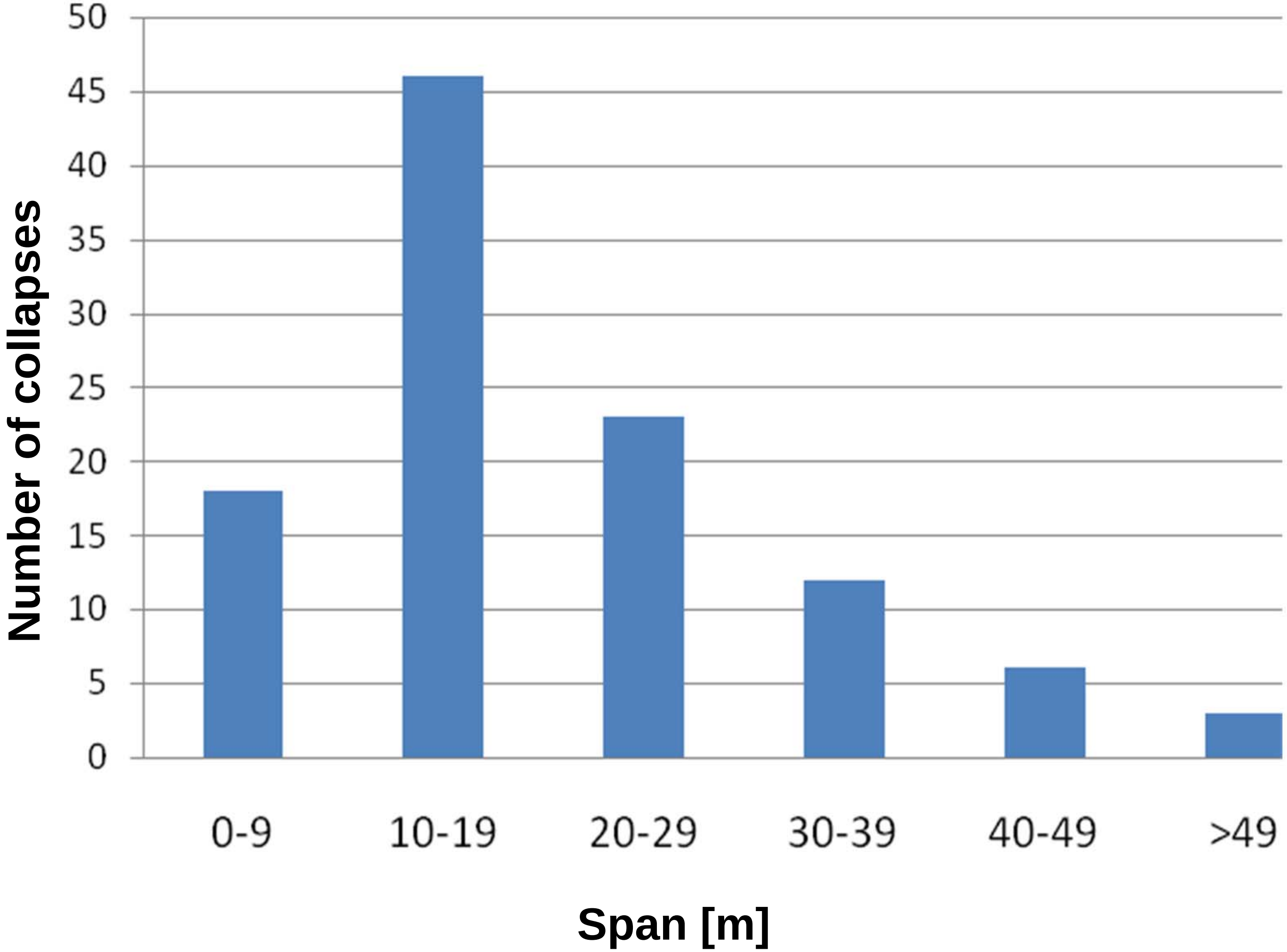
Structural material

42 % steel

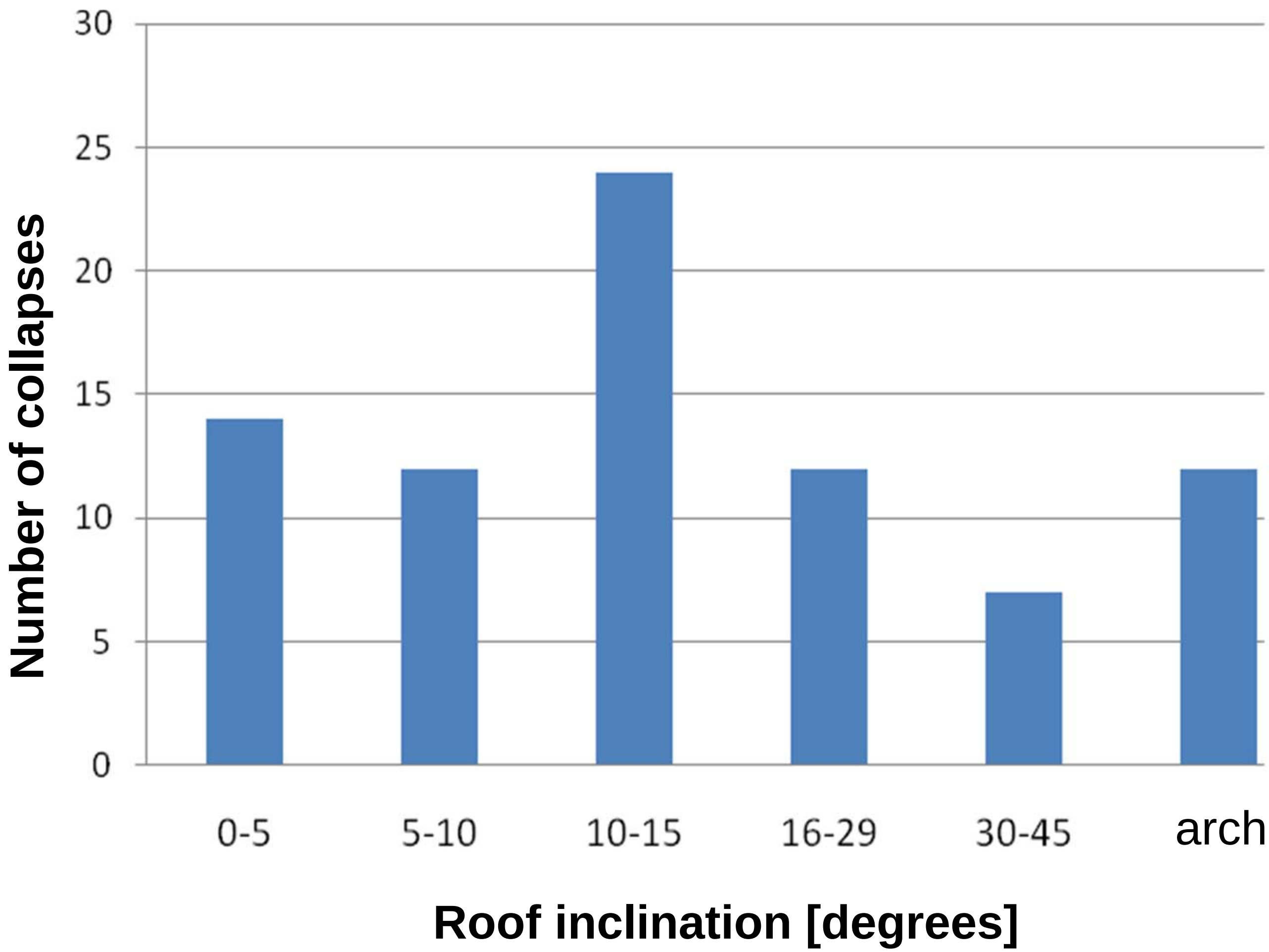
47 % timber

11 % glulam

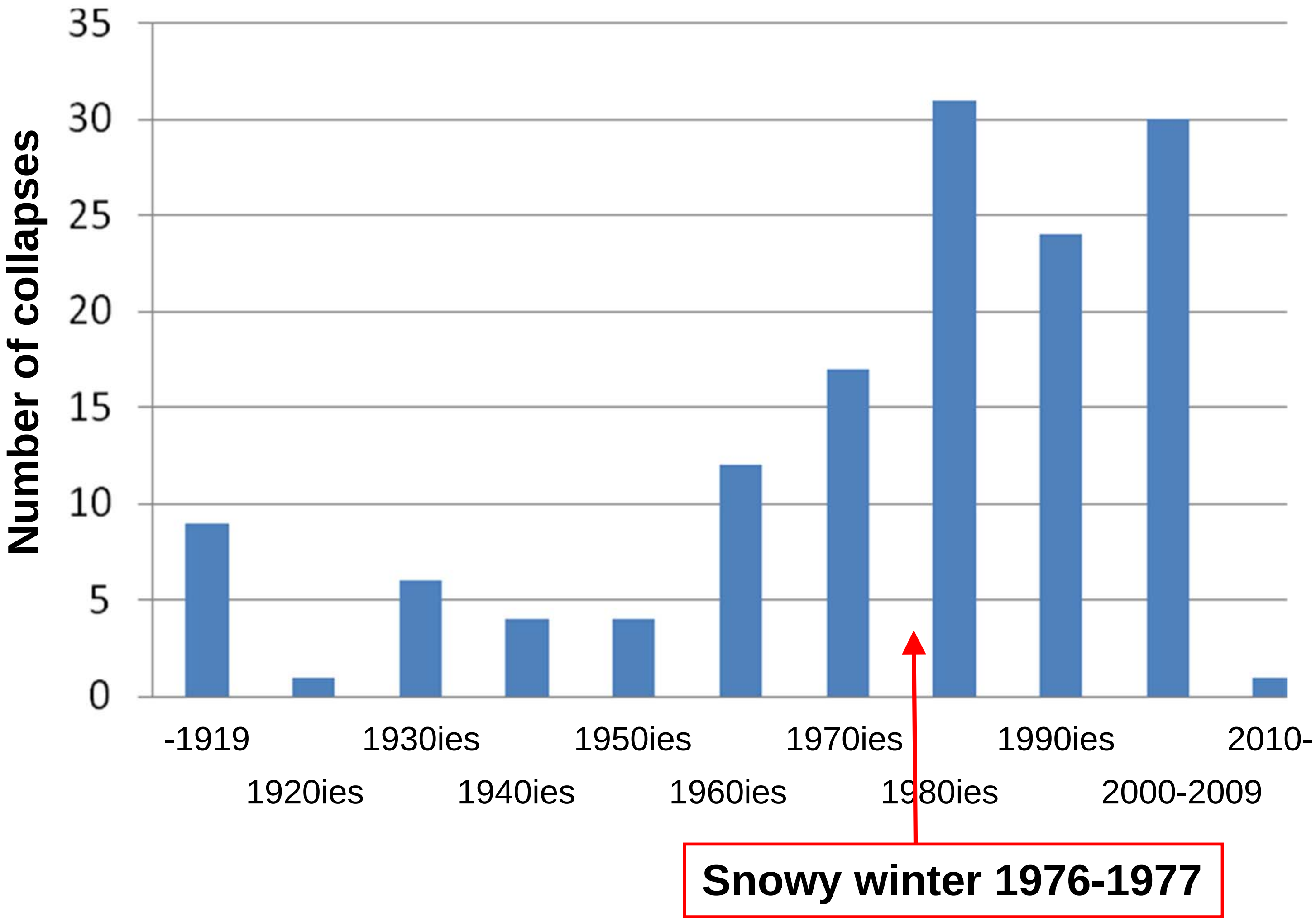
Span


50
45
40
35
30
25
20
15
10
5
0
Number of collapses
0-9
10-19
20-29
30-39
40-49
>49
Span [m]

Roof inclination

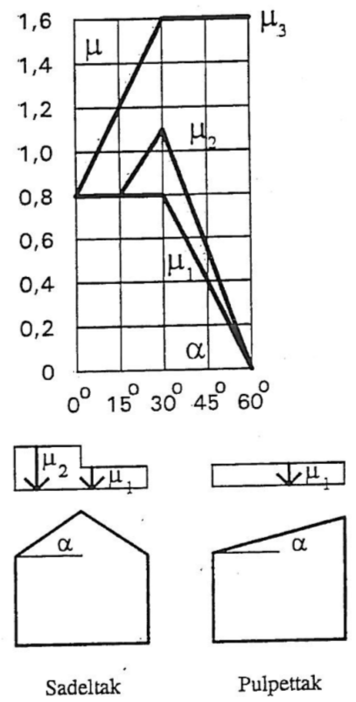


Age of Structure (year of completion)



Observations regarding snow loads

- Not more snow than in the code (1 exeption)
- No occasional thawing and wind from north/east during the whole snowing period led to large snowdrifting →highly nonsymmetrical snowloads
- Nonsymmetrical snow loads even for roofs with low inclination (not at all in Swedish standard; non-symmetry larger than in Eurocode)
- Measured snow load on roof equals snow load on ground (in the standard, a form factor of 0.8 is used?!)
- Large differences in snow depth for large roofs



Reasons for collapse (37 cases)

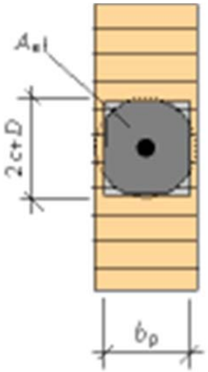
Structural material	Errors in / lack of design	Errors in material / compo-nent	Lack of main-tenance	Errors on building site	Other (e.g. snow load)
Steel (beam, frame, arch)	8	1	-	3	5
Glulam (beam, frame)	3	2	-	4	3
Timber (framework/lattice)	5	1	2	4	3
Sum	16	4	2	11	11
%	43	11	5	30	30
Nordic study (2007) %	53	11	*	27	9

No statistics for whole sample (170 cases) available

Reasons for failure in collapsed timber and glulam structures

- **Timber structures**
  - Missing stabilizing elements
  - Rot (lack of maintenance)
  - Purlin as gerber system – very sensitive to varying loading in different spans
- **Glulam structures**
  - Risk for lateral buckling neglected
  - Cracks in tension rod (steel quality)
  - Missing anchor plate in tension rod connection
  - Tension failure in tension rod
  - Wrong detailing of tension rod connection

Critical aspects in glulam structures
Example 1: error on building site



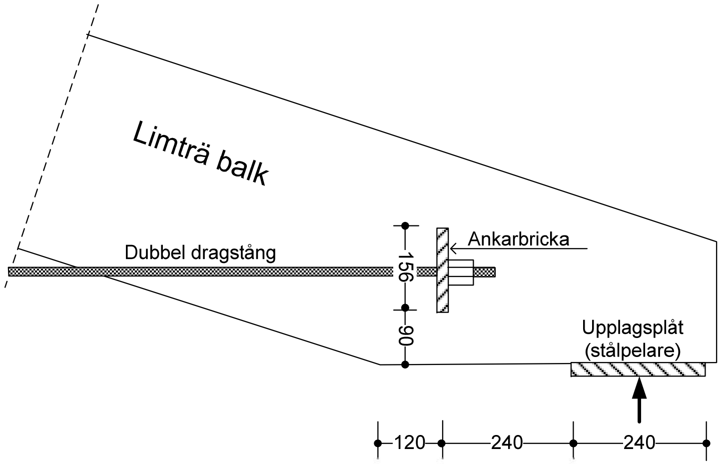
Three-hinged frame, tension rod

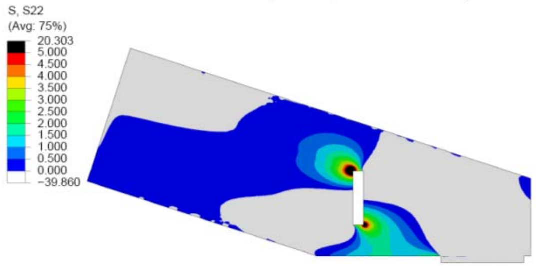
Anchor plate dimensions
115x 55x 25 mm^3

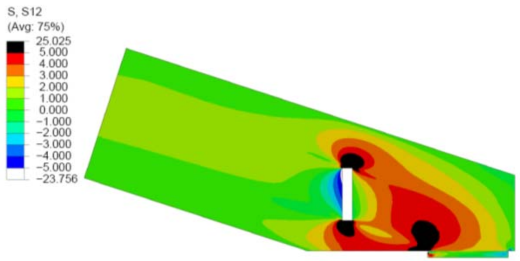
Missing anchor plate leading to the nut being drawn through the glulam beam

Collapse after 18 years

Critical aspects in glulam structures
Example 2: error of design







Eccentricity between tension rod connection and steel column

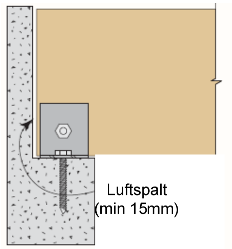
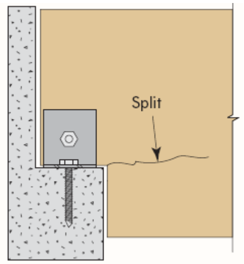
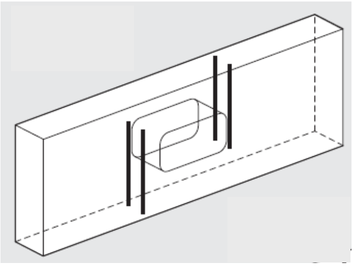
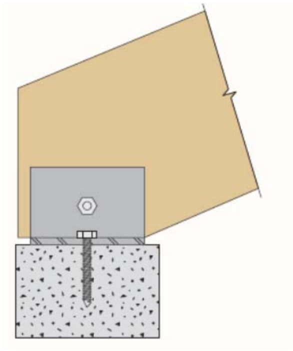
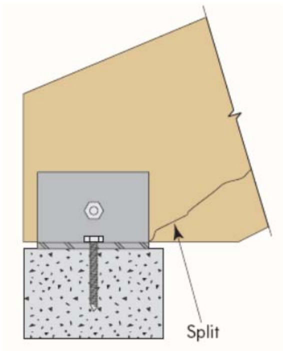
→high tension stresses perpendicular to grain

→ High shear stresses

Modelled by Henrik Danielsson,
Structural Mechanics, Lund University

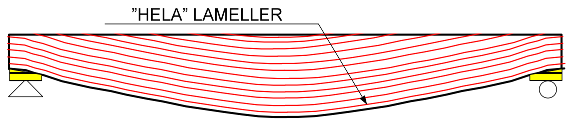
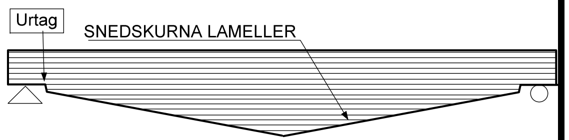
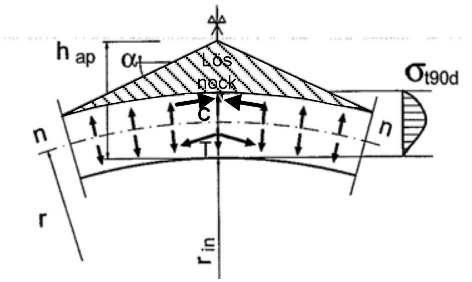
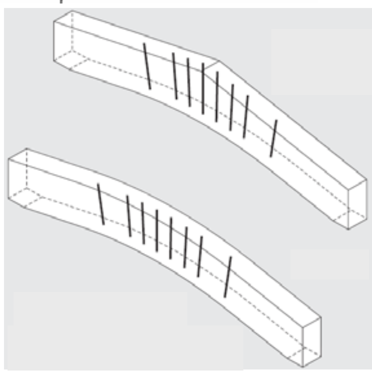
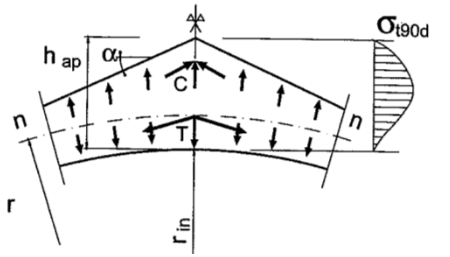
Critical aspects in glulam structures (general)

as presented in the report

	GOOD / BETTER	BAD / WORSE
Notched beams		
Holes		
Too short support length for inclined beams		

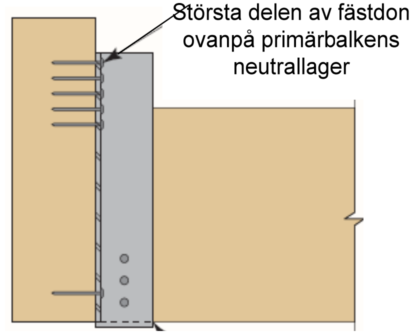
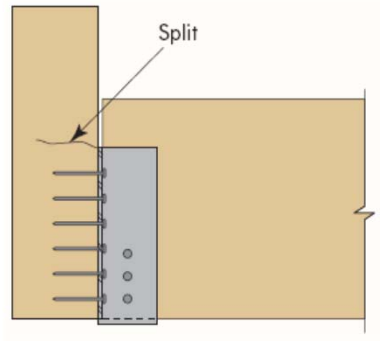
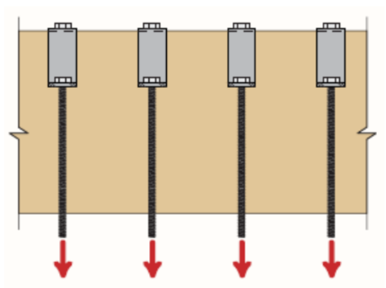
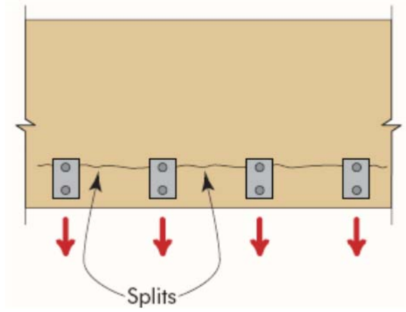
Critical aspects in glulam structures (general)

as presented in the report

	GOOD / BETTER	BAD / WORSE
Cut lamellae for tapered beams		
Tension perpendicular to grain in special beams	Loose ridge  Screw Reinforce-ment 	

Critical aspects in glulam structures (general)

as presented in the report

	GOOD / BETTER	BAD / WORSE
Design of joints *Primary / secondary beam*		
Loading perpendicular to the grain		

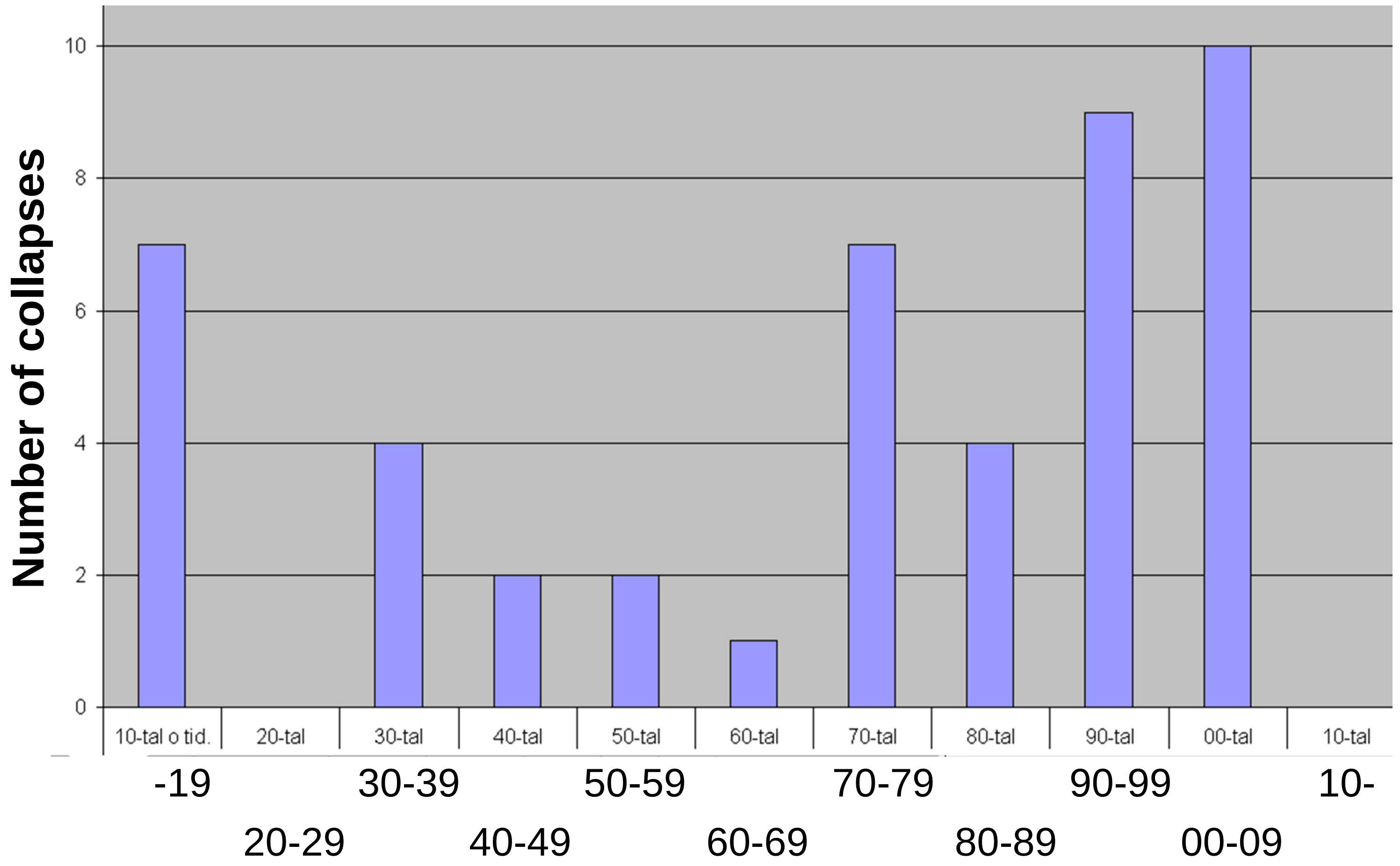
Agricultural buildings

- Special rules for agricultural buildings
  - No building permit required
  - 15% higher capacity of nailed connections

- 63 collapsed agricultural buildings in SP database

- Building material
  - 70% Timber framework
  - 10% Timber traditional 2-storey building
  - 5% Glulam
  - 15% Steel

Agricultural buildings - Age (year of completion)



Agricultural buildings – Design

- Difficult to say whether there was any design at all or who did the design

- ”in some cases the design was right which does not help much if other parts are wrongly designed or are missing…”

- Timber framework: stabilizing elements are often missing (missing in design or error on building site)

- Purlins often designed as continuous beams, but built as single span beams – purlins have too low capacity and cannot really stabilize the building against buckling and lateral buckling

Agricultural buildings – loads

- Snowload often highly non-symmetric
- Non-symmetric snowload due to snow removal, leading to collapse in one case
- Many buildings close to each other – snow from roofs with high inclination falls down on roofs with lower inclination → low inclination roof should be designed to withstand 50% of the other roofs snowload

Agricultural buildings – reasons for collapse (10 cases)

Structure TF = timber framework T2 = timber 2-storey	Span [m]	Inclination [degr.]	Errors in / lack of design	Errors in material / component	Lack of main-tenance	Errors on building site	Snow differently distributed on roof compared to code	Higher snowload on roof compared to code when completed
TF	34/2	10	X					
TF	31/2	10	X	X		X		
TF	20/2	14					X	X
T2	14	45			X			
TF	14	23					X	
TF	32/2	15	X			X	X	
Glulam	18	15	X				X	
TF	15	10	X					
TF	16	16					X	
Steel	14	14	X				X	
%			60	10	10	20	60	10

➡ **Errors in design / lack of design**
Snow distribution on the roof

Danish experience of collapses of agricultural buildings 2010

- Ventilation hoods on the roof lead to snow accumulation on the leeward side
- Insurance company checked 60 buildings, only 9 were OK (free from mistakes)
- Typical errors
  - Wrong bracing
  - missing bracing (sometimes despite notation on the girder where to place the bracing)
  - bracing not tightened
  - bracing cut off
  - Wrong execution of nailed connections

Interviews with suppliers (steel, sheathing, glulam)

- What type is the collapsed structure – is that type still used or was the design changed?

- Control of design of collapsed structures with old and new codes – difference in some cases due to higher snow loads / non-symmetric snow loads and use of Eurocode

- Typical errors according to suppliers
  - removed tension rods
  - corrosion due to lack of maintenance
  - new building generating snow pockets
  - Notches/holes in glulam beams made on building site (not in the design) → information leaflet on holes and notches follows the delivery
  - Collapse of steel sheathing above the primary beams due to high bending moment and high support reaction (now designed with larger safety margin, instructions for snow removal on homepage)

Interviews with suppliers (steel, sheathing, glulam)

- Typical problems according to suppliers
  - communication between the different designers (errors in design of stability and supports, information on snow pockets etc)
  - Communication between designers and suppliers
  - Lack of information from client to supplier → difficult to make good design

- Sensitive structures/elements according to suppliers
  - Arches
  - Gerber systems
  - Large deformations
  - Fracture at support

Conclusions and proposals for action:
Collapses

- Slender roof structures (steel, timber, glulam) have collapsed
- > 60% of collapsed buildings were built from 1980 and on
- Low inclination (in 50% of the cases < 15 degrees)
- Reasons for failure (from thorough study of 37 cases)
  - No design /wrong design (including neglected snow pockets): 43%
  - Errors on building site: 30%
  - Material or component: 11%
  - Lack of maintenance: 5%
  - Other (including overload of snow): 30%

Conclusions and proposals for action:
Agricultural buildings

- Mostly timber roofs
- Reasons for collapse mostly carelessness and ignorance
- Often built without competence (do it yourself)
- Often no design at all
- Proposals for action:
  - Inform farmers about the responsibility to be commissioner of a building project by broschures and seminars
  - Request from insurance companies that they require control and supervision

Conclusions and proposals for action:

Snow load and form factors

- Value of snow load was increased for 2/3 of places in 2006 (decreased in only few cases)
- Snow load in current standard is plausible
- Form factors
  - For roofs with low inclination (<15 degrees), the standard prescribes symmetrical load, however, in reality the snowload was highly nonsymmetrical → introduction of Eurocode will improve this, but is that enough?
  - Snow load on flat roof = 80% of snow load on ground – WHY?
- Proposal for action: investigate form factors for snow load

Conclusions and proposals for action:

Weaknesses of different constructions

- Steel: Slender structures need to be properly stabilized (needs good design and execution)
- Glulam: local stresses (notch, slotted-in plate)
- Nailplate timber roofs: lack of bracing of compressed elements
- Steel arch covered with textile: lack of bracing against lateral buckling
- Roof sheathing: gerbersystems sensitive to nonuniform loading; should be designed in highest safety class (usually in medium); sheathing is often too thin
  → proposal: inform on correct design of sheathing
- Risk for progressive collapse is often neglected
- Proposal for action: formulate a broschure on weaknesses of different roof types (primary/secondary elements, detailing, risk for progressive collapse)

Conclusions and proposals for action:

Design programs

- Many different programs
- Suppliers have own programs
- Programs are based on different models
- Many programs do not consider important load combinations

Conclusions and proposals for action:
How many contractors?

- No difference whether one or several contractors
- Lacks in design and execution
- lack of compentence for some contractors
- Who has overall responsibility when many contractors?

Conclusions and proposals for action:

Building permit process

- Depending on when the building was erected, different meetings/control plans were needed
- Usually, the meetings were held, control plans were agreed upon – but not specified what is checked in the control plan, no documentation
- Need for a competent person linking all the different contractors, which only have responsibility for their part
- Different checks are missing, e.g. control of effect of snow pockets

- Conclusion: Collapses could not have prevented even if all rules had been followed

- Proposals for action
  - Control plan should include more technical information
  - One responsible designer / expert needed to put together all pieces
  - Reconstruction/extension of buildings: design should include both old and new parts
  - Different parts from different suppliers: make sure that the different parts interact correctly

References

- Report: Roof collapses winter 2009/2010 and 2010/2011 – reasons and proposals for actions; Carl-Johan Johansson, Camilla Lidgren, Christer Nilsson, Roberto Crocetti; Draft 2011-05-10