Analysis of failures in timber structures based on a Nordic project

Eva Frühwald, LTH

LUND INSTITUTE OF TECHNOLOGY
Lund University

project title: Innovative design, a new strengh paradigm for joints, QA and reliability for long-span wood construction

- financed by Vinnova (Sweden) and Tekes (Finland) as well as several companies
- 2004-2007
- partners
  - Sweden: LTH, Växjö university, SP, Limträteknik AB
  - Finland: VTT
- project parts
  - Performance of high capacity dowel type and rubber joints – Effect of short-term and long-term loading, of moisture and innovative design (VTT, LTH-Structural Mechanics, Växjö university, SP)
  - Reliability and competence in timber construction (LTH-Structural Engineering, VTT, SP, Limträteknik AB)
  - Quality assurance of timber construction based on failure experience (VTT)

project title: Innovative design, a new strengh paradigm for joints, QA and reliability for long-span wood construction

- financed by Vinnova (Sweden) and Tekes (Finland) as well as several companies
- 2004-2007
- partners
  - Sweden: LTH, Växjö university, SP, Limträteknik AB
  - Finland: VTT
- project parts
  - Performance of high capacity dowel type and rubber joints – Effect of short-term and long-term loading, of moisture and innovative design (VTT, LTH-Structural Mechanics, Växjö university, SP)
  - Reliability and competence in timber construction (LTH-Structural Engineering, VTT, SP, Limträteknik AB)
  - Quality assurance of timber construction based on failure experience (VTT)

report

1. Introduction
2. Experience from previous failure investigations
3. Survey of failure cases – methodology
4. Results and interpretation of the information collected
5. How can we learn from previous failures?
6. Summary and conclusions

Appendix

Report TVBK-3053
ISSN 0349-4969
ISNR:LUTVDG/TVBK-3053-SE (yy p.)

Draft

Design of safe timber structures –
How can we learn from structural failures in concrete, steel and timber?

Eva Frühwald
Tomi Toratti
Sven Thelandersson

Erik Serrano
Arne Emilsson

Lund University
Division of Structural Engineering
Box 118
SE 22100 Lund, Sweden

Telephone: +46 46 222 9503
Fax: +46 46 222 4212
www.kstr.lth.se

appendix

- overview with classification
- 127 failure cases, 1-2 pages per case (162 pages)

case	material	Failure reason and index*									source
		1	2	3	4	5	6	7	8	9	
1	ST					1					LS
2	ST				0.2		0.8				LS
3	GL						1				LS
4	GL						0.5	0.5			LS
5	GL	0.1				0.2	0.4	0.3			LS
6	GL					0.8		0.2			LS
7	GL					0.8	0.2				LS
8	GL					1					LS
9	GL					0.5	0.5				LS
10	GL					1					LS
11	ST	0.1				0.4		0.5			LS
12	GL					0.5		0.5			LS
13	plywood							1			LS
14	GL						1				LS
15	ST							1			LS
16	Plywood, ST							1			LS
17	ST						1				LS
18	ST					0.7		0.3			LS

Case 108 – Cracking in tapered glulam roof beams

Description of structure

The building is a sports hall, erected in 1988. The roof structure consists of seven double tapered roof beams, approximately 655 mm deep at the supports and 1300 mm deep at mid-span. The beam width is 185 mm. The beams have a span of approximately 20 m, and are placed with a spacing of 5 m. The roof is made from self-supporting corrugated steel sheets.

Description of failure

At a building inspection it was noticed that extensive cracking had occurred in several beams. This lead the inspecting consultant to recommend an extended inspection to be performed by SP.

Original investigation performed and conclusions

The beams are visible from the inside of the building and were inspected by SP personnel. Apart from geometrical data of the beams the moisture content was measured, and found to be in all cases below 10%. The beams were manufactured with a dark coloured adhesive. All beams were inspected for cracking, although not all parts of all beams were inspected. The parts inspected were selected amongst those parts showing the most severe cracking, as was visible from the floor level. This means that the parts not inspected are likely to have less severe cracking.

The original investigation gives a rather detailed view of the cracks. The conclusions were that, apart from drying cracks which are normal in glulam, there were about 10 cracks 1-8 m long and 30-70 mm deep, which could not be explained by drying alone. The most severe crack of these was one starting at the support and reaching about 6-7 m, running all the way in an interlaminar bond line. This crack was found on both sides of the beam, and on one side it had been filled with adhesive at the production. The crack depth was measured to be more than 70 mm on one side and at least 10 mm on the other side (the depth of the repair was 10 mm). In several cracks there was evidence that the adhesive had started to cure too much before appropriate pressure had been applied.

The conclusion was that the severe cracks were due to manufacturing errors (too long open assembly time), and that the shear capacity of the beams should be re-evaluated, taking into account the crack depths and lengths.

Additional conclusions and comments

The conclusions from the original investigation seem adequate. The failure can be classified as being due to manufacturing error, related to a too long open assembly time.

why should we learn from previous failures / collapses ?

Hypothesis:
All failures are caused by human errors.

- **Errors of knowledge** (inadequate training in relation to tasks)
- **Errors of performance** (non-professional performance, carelessness)
- **Errors of intent** (consciously taking short-cuts and risk to save time/money)

[Kaminetzky]

previous studies: common failure causes

- **concrete**
  - material quality (concrete mix, impurities, cement type,...)
  - work execution (vibration, placement of rebars, removal of formwork,…)
  - structural design and detailing (joints, openings, supports,…)
- **steel**
  - insufficient temporary bracing during construction
  - errors in design / construction mainly of connections and details
  - deficient welding
  - excessive flexibility and nonredundant design
  - Vibration induced failures
  - stability type failures
  - fatigue and brittle failure
  - corrosion damage
- **timber**
  - inadequate behaviour of joints
  - effects of moisture exposure (imposed strains, shrinkage)
  - poor durability performance
  - inadequate bracing of structural system
  - inadequate performance of material and products
  - inadequate appreciation of load

previous studies: common failure causes

- **concrete**
  - material quality (concrete mix, impurities, cement type,...)
  - work execution (vibration, placement of rebars, removal of formwork,…)
  - **structural design and detailing (joints, openings, supports,…)**
- **steel**
  - **insufficient temporary bracing during construction**
  - **errors in design / construction mainly of connections and details**
  - deficient welding
  - excessive flexibility and nonredundant design
  - Vibration induced failures
  - stability type failures
  - fatigue and brittle failure
  - corrosion damage
- **timber**
  - **inadequate behaviour of joints**
  - effects of moisture exposure (imposed strains, shrinkage)
  - poor durability performance
  - **inadequate bracing of structural system**
  - inadequate performance of material and products
  - inadequate appreciation of load

survey of failure cases

- survey
  - literature (L)
  - own investigations (I)

- partners — number of cases

Partner		Number of cases
Limträteknik AB, Falun (I)		12
LTH	(L)	67
SP	(I)	18
VTT	(I,L)	30

→ total of **127 cases**

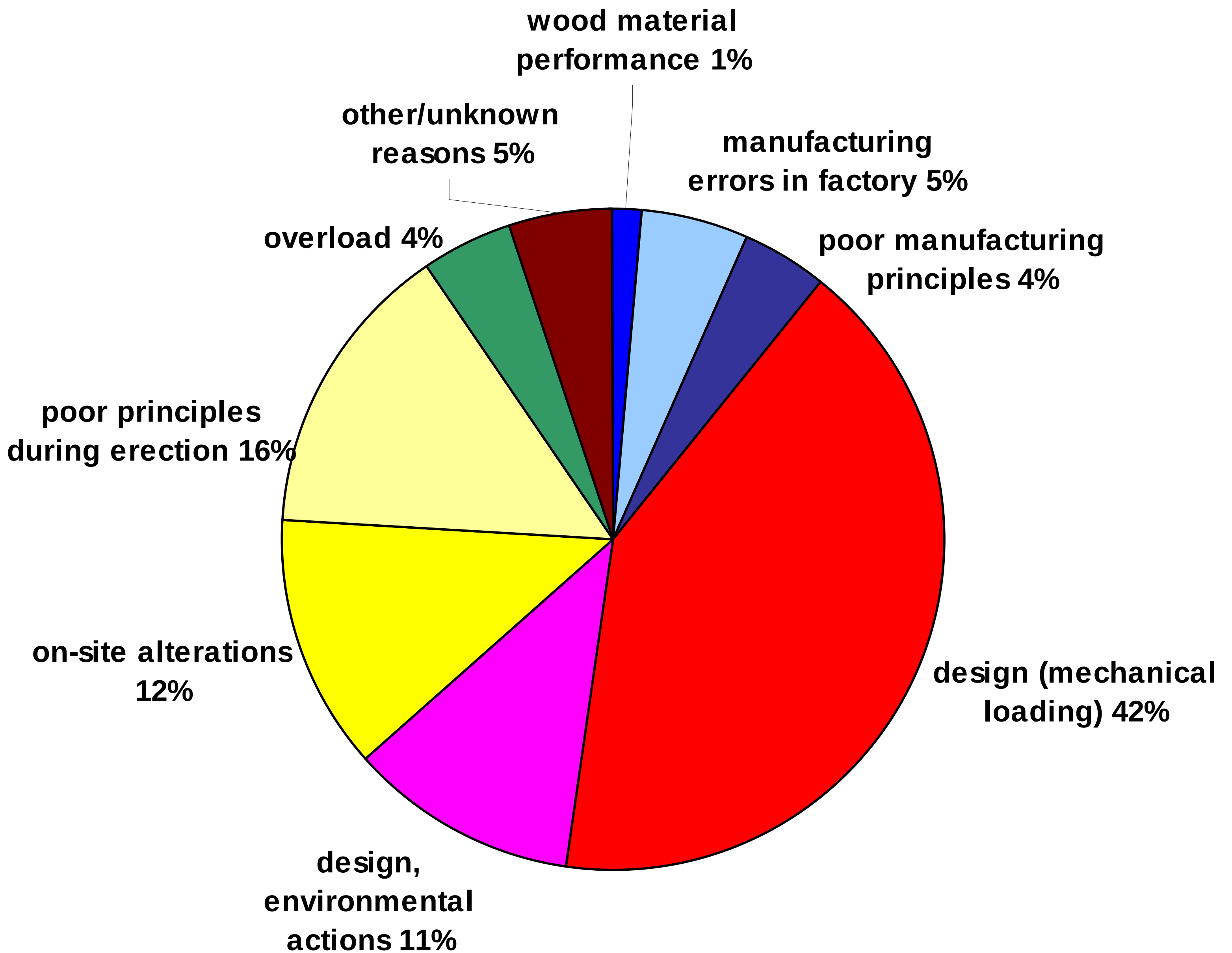
categories of failure causes

1. Wood material performance
2. manufacturing errors in factory
3. poor manufacturing principles
4. on-site alterations
5. poor principles during erection
6. poor design / lack of design with respect to mechanical loading
7. poor design / lack of design with respect to environmental actions
8. overload in relation to building regulations
9. other / unknown reasons

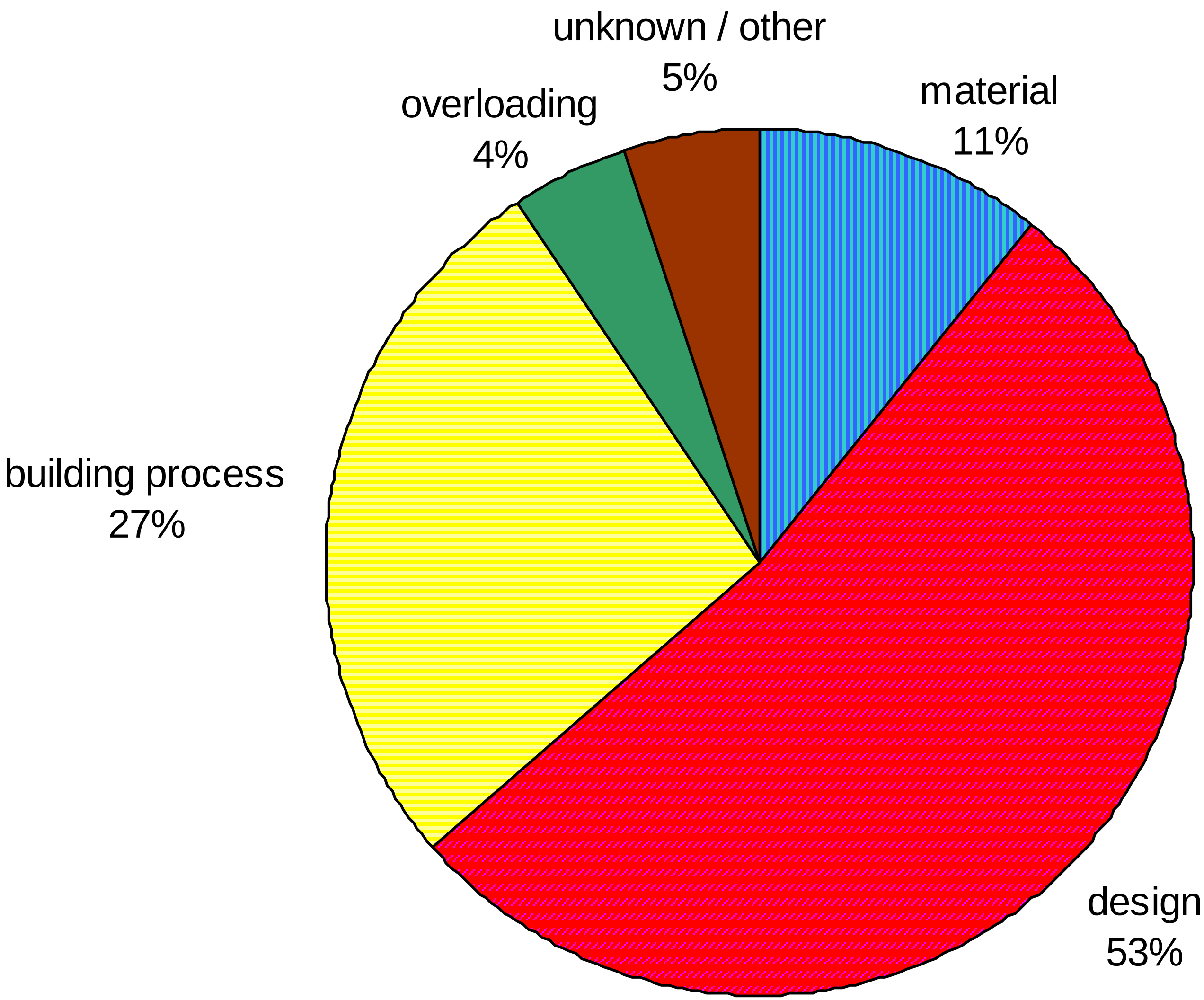
failure cause – one or more categories (multiple failure causes)

case	material	Failure reason and index*									source
		1	2	3	4	5	6	7	8	9	
1	ST					1					LS
2	ST				0.2		0.8				LS
3	GL						1				LS
4	GL						0.5	0.5			LS
5	GL	0.1				0.2	0.4	0.3			LS
6	GL					0.8		0.2			LS
7	GL					0.8	0.2				LS
8	GL					1					LS
9	GL					0.5	0.5				LS
10	GL					1					LS
11	ST	0.1				0.4		0.5			LS
12	GL					0.5		0.5			LS
13	plywood							1			LS
14	GL						1				LS
15	ST							1			LS
16	Plywood, ST							1			LS
17	ST						1				LS
18	ST					0.7		0.3			LS

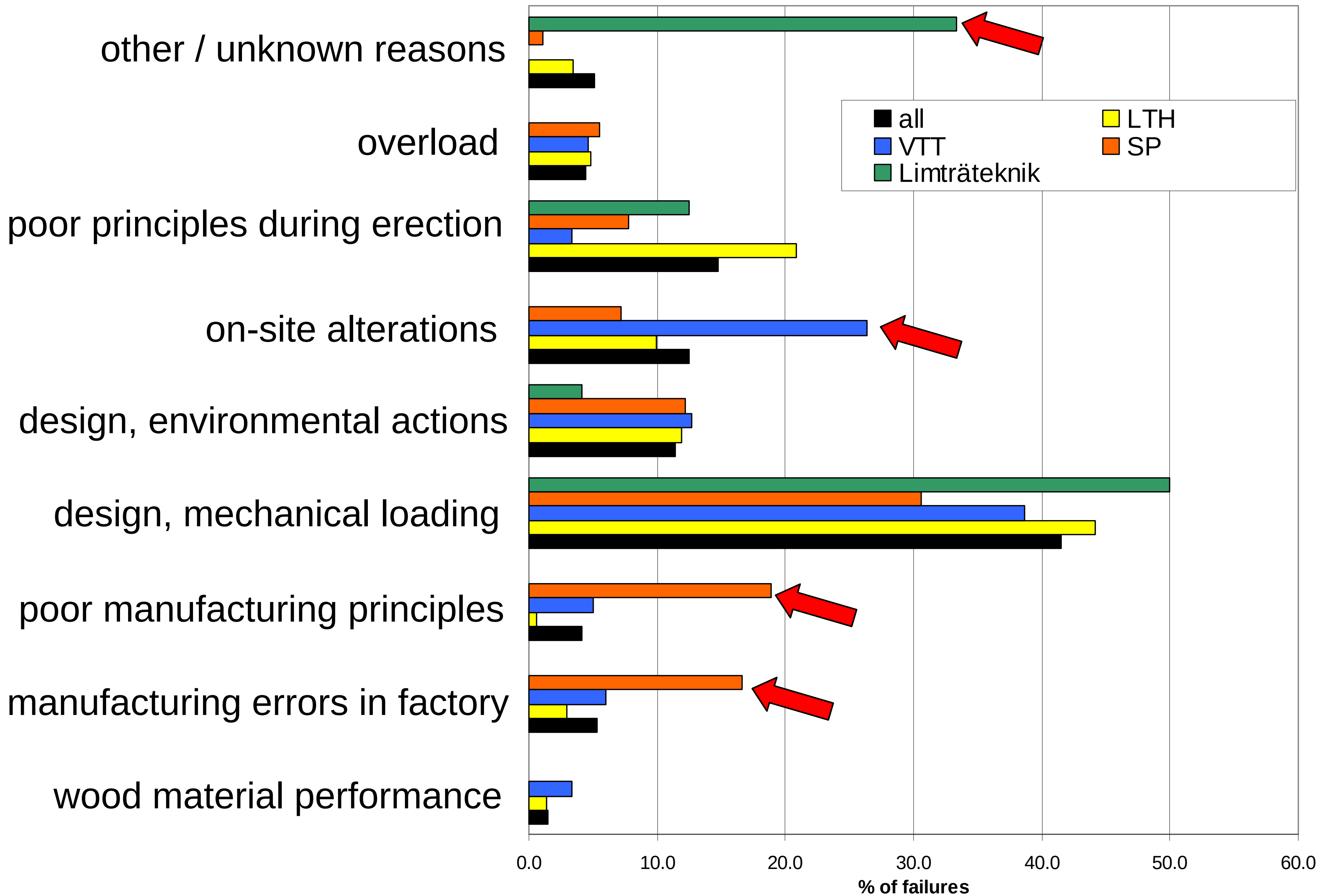
failure cause (127 cases)



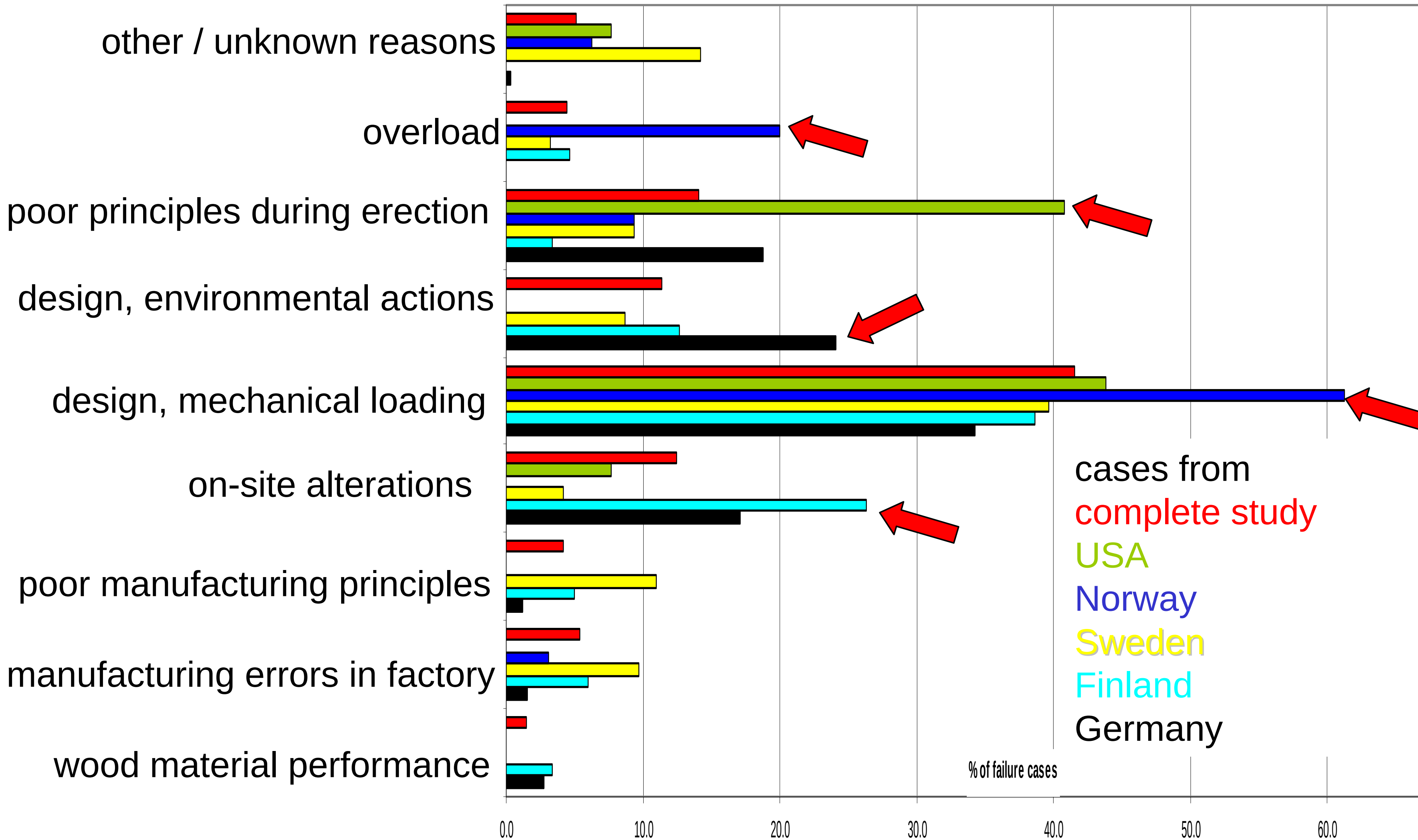
failure cause (127 cases)



failure causes for different parts of the case study



failure causes for different countries

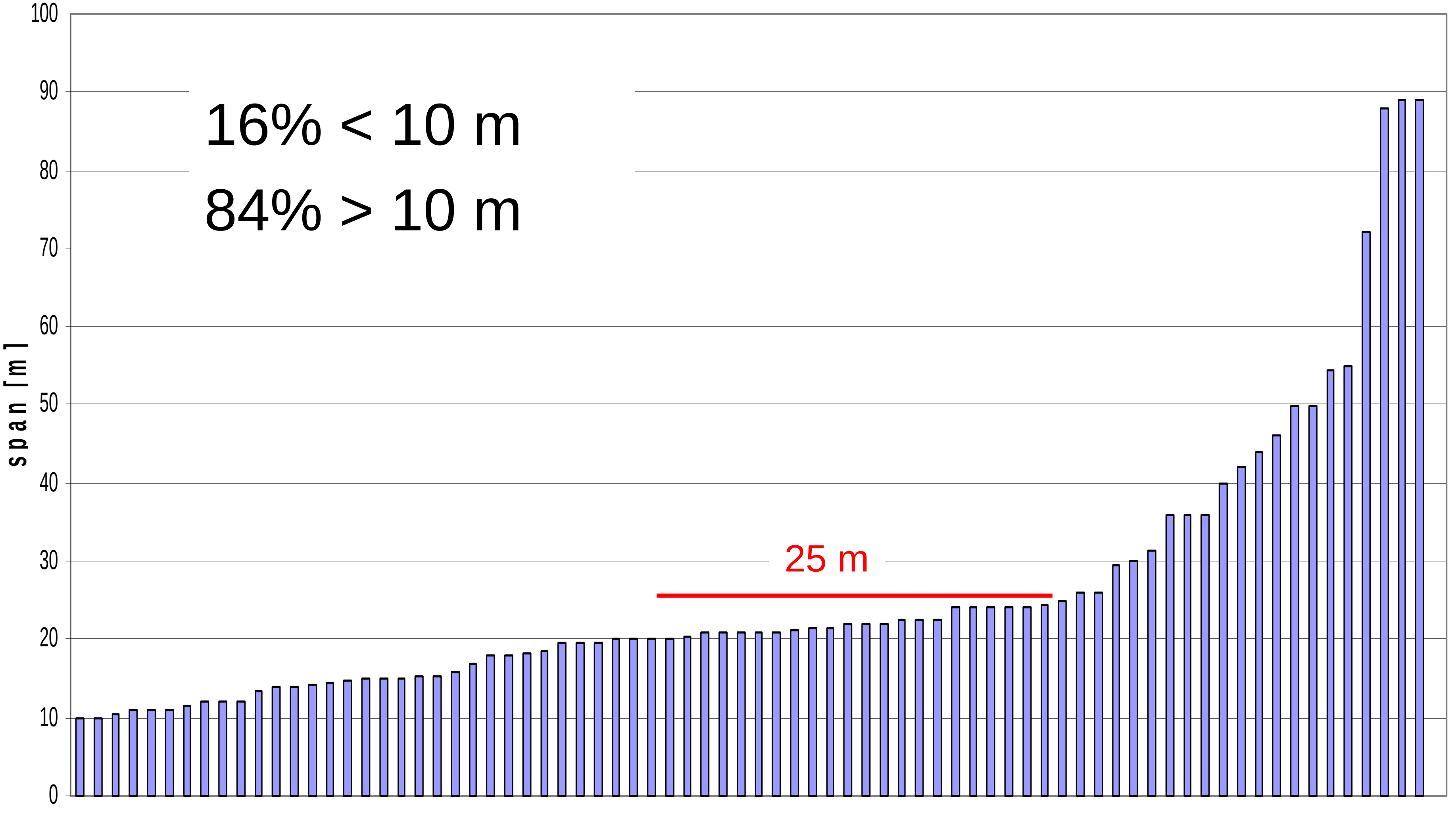


type of buildings

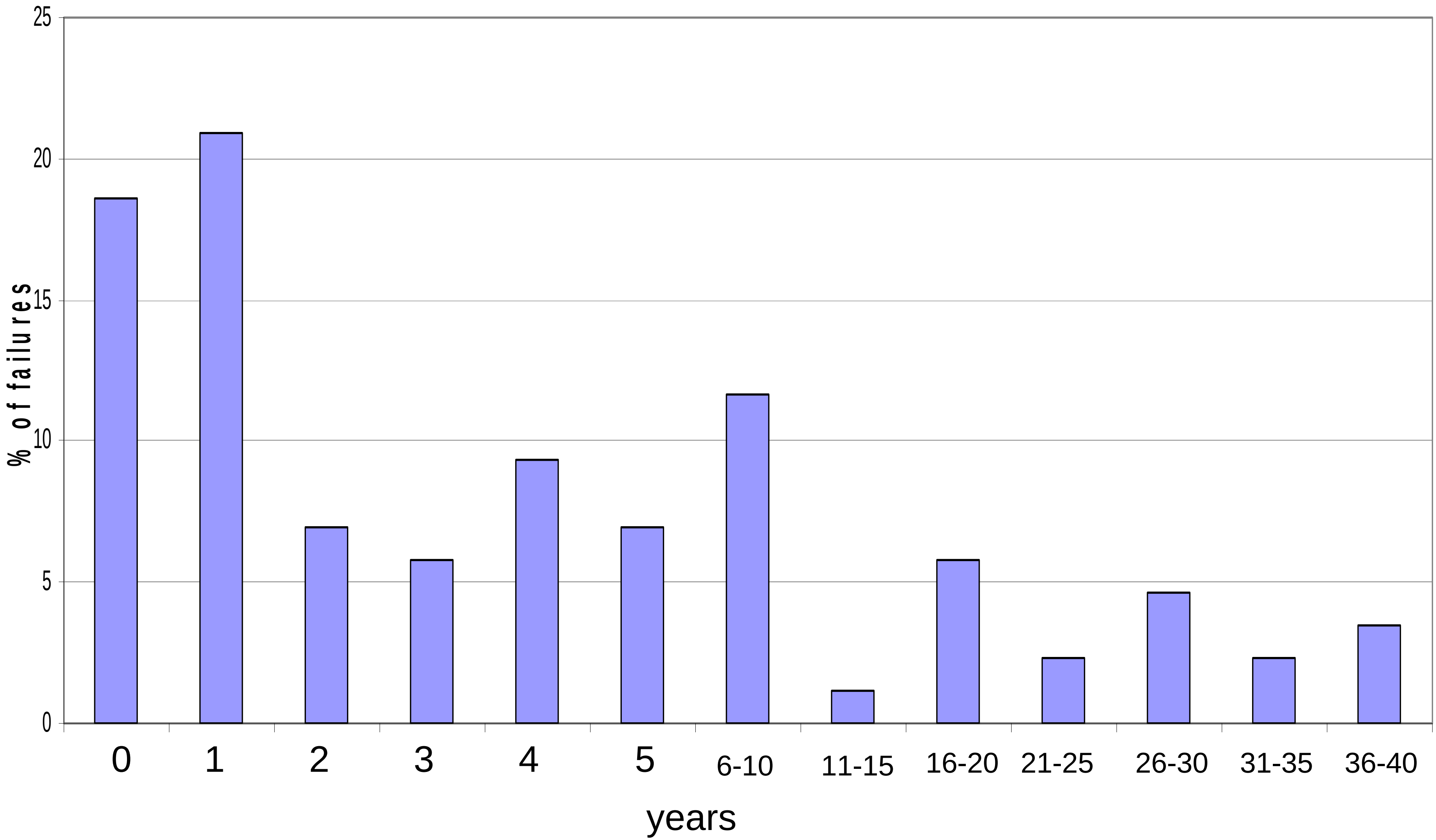
	in percentage of cases
public	51
industrial	23
agricultural	7
apartment	8
other / unknown	11

- better investigation / media coverage on failures in public buildings compared to private buildings
- focus on large-span structures (mostly public or industrial)

span



age at failure



type of structural elements that failed

	in percentage of cases
beam	47
truss	34
bracing	29
joint	23
arch	8
column	4
frame	2

Joint breakdown:

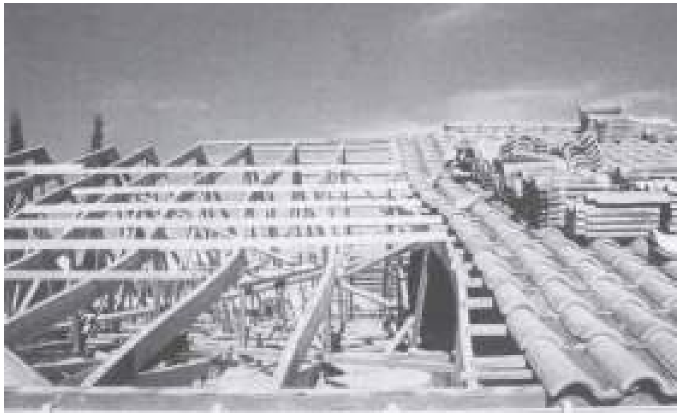
dowel-type	57
punched metal plate	10
glued	7
other	27

correlated with typical structural elements?!

failure modes

in decending order of importance…

	in percentage of cases
• **instability**	**30**
• bending failure	15
• tension failure perp. 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 (buckling)	2
• other / unknown	21



timber, steel and concrete buildings: failure causes

Failure cause [in % of cases]	Timber [own survey]	Steel [2]	Concrete [3]
Design	53	35	40
Building process	27	25	40
Maintenance / reuse		35	
material	11		
other	9	5	20

difficult to compare – definition of categories, number of cases etc.

→ Question: Are engineers better at designing steel- and concrete structures !?

How can we learn from previous failures?

53 % design errors
27 % building site errors

human errors

Errors of knowledge
(inadequate training in relation to tasks)

Errors of performance
(non-professional performance, carelessness)

Errors of intent
(consciously taking short-cuts and risk to save time/money)

improved training and education

more efficient Quality Assurance (QA)

more efficient Quality Assurance (QA) ?

Training & education

- should focus on technical aspects which are typical causes for failure

- training of engineers and control in the design phase most important (as most errors are made in this phase)

- training & education measurements
  - lectures on good and bad examples for students / engineers
  - database on good / bad examples
  - …

  → learning from each others mistakes

Training & education: examples for issues to be emphasized

- bracing to avoid instability both in the finished structure and during construction
  - planning of the erection sequences to minimize risks
  - giving clear instructions to the construction workers on how to provide temporary bracing
  - more careful work preparation needed on building site
  - practical guidelines showing how to design for sufficient bracing
  - relevant requirements for load-bearing capacity and stiffness of structures used for bracing should be included in codes

- situations with risk for perpendicular to grain tensile failure (joints, double-tapered beams, curved beams,…)
  - improve knowledge about consequences of strength anisotropy and shrinkage properties
  - include control of risk for perpendicular to grain failure in design control procedures, at least for large-scale timber structures (perhaps in combination with moisture effects)

Training & education: examples for issues to be emphasized

- consideration of moisture effects
  - special controls/checks to evaluate the effects of unavoidable moisture movements in the structure, especially in sections where moisture movement is restrained
  - moisture effects should have high priority as an issue in
    - education of timber engineering
    - design of control systems

Training & education: examples for issues to be emphasized

- design of joints
  - problems in dowel-type joints
    - stress transfer very complex
    - wood anisotropy
    - risk of stresses perpendicular to grain
    - excentricities may lead to higher stresses than global structural analysis
    - dowels may reduce timber cross section significantly
  - checklist
    - stresses perpendicular
    - excentricities
    - net area (minus holes, slots)
    - stress transfer in dowel-type fasteners
    - angle between force and fiberdirection,…
  - careful and controlled execution in manufacturing and construction necessary
  - design of timber joints should be of priority in
    - timber engineering research
    - education
    - Quality Assurance procedures

Training & education:
examples for issues to be emphasized

- appreciation of loading conditions
- appreciation of real behaviour of the structure

} when designing all materials

- increasing the competence of building site professionals
  - professional training
  - assigned training / certified personnel to perform certain tasks
  - continuous courses and seminars
  - external quality control by impartial and certified personnel

Literature / references

[1] Kaminetzky, D.: Design and Construction failures - lessons from forensic investigations, McGraw-Hill, 1991

[2] Peter Oehme & Werner Vogt: Schäden an Tragwerken aus Stahl, Schadenfreies Bauen Band 30, Hrsg. G. Zimmermann & R. Runau, Fraunhofer IRB Verlag, 2003

[3] Bernhard Brand & Gerhard Glatz: Schäden an Tragwerken aus Stahlbeton, 2. erweiterte Auflage, Schadenfreies Bauen Band 14, Hrsg. G. Zimmermann & R. Runau, Fraunhofer IRB Verlag, 2005

[4] Feld & Carper: Construction Failure, Wiley, 1997

Pict.

- Hans-Jörgen Larsen
- Timber Engineering, STEP 2, 1995
- G. Dröge & T. Dröge: Schäden an Holztragwerken, Schadenfreies Bauen Band 28, Hrsg. G. Zimmermann, Fraunhofer IRB Verlag, 2003
- ”Der Spiegel” www.spiegel.de